MODE LOCKED OPTICAL KLYSTRON CONFIGURATION IN AN FEL CAVITY RESONATOR

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Neil Thompson, ASTeC, STFC, Daresbury Laboratory
Outline

• Mode Locked Optical Klystron - brief review

• Further development:
  MLOK in an cavity resonator
  – RAFEL without MLOK – interesting case of short electron pulse: $l_b \sim l_c$
  – RAFEL with MLOK – short electron pulse
  – IR-FEL cavity resonator with MLOK

• Conclusions
Mode Locked Optical Klystron – brief review
Axial Modes from an *amplifier* FEL

- *Synthesise axial mode spectrum without cavity*

![Diagram showing electron delay and slippage](image)

- Each undulator/chicane module has been synthesized
For continued slips of distance $s$, only those wavelengths with an integer number of periods in distance $s$ will survive after many such slips. For $s$ an integer of $\lambda_r$:

$$s = N \lambda_r = (N + 1) \lambda_-$$

$$\Rightarrow \omega_r = \frac{2\pi c N}{s}; \quad \omega_+ = \frac{2\pi c (N + 1)}{s} \quad \Rightarrow \Delta \omega_s = \omega_+ - \omega_r = \frac{2\pi c}{s}$$
X-ray SASE MLOK amplifier with mode-locking*

Spike FWHM ~ 23 as

*Thompson, McNeil, PRL 100, 203901 (2008)
Amplified HHG – retaining structure with MLOK via initial electron beam energy modulation*

Figure 6: Longitudinal intensity profile (top) and spectral power distribution (bottom) of the HHG seed in 3D simulations.

Improved temporal coherence by increasing cooperation length*

Figure 3: Short Pulse Regime: Scaled power pulse profiles at saturation for (a) $S_e = 1.0$ and (b) $S_e = 4$ with delays randomised and terminated prior to saturation.

*Thompson, Dunning & McNeil, IMPROVED TEMPORAL COHERENCE IN SASE FELS Proceedings of IPAC’10, Kyoto, Japan, TUPE050, 2010
Why bother with APTs?


Further development: MLOK in an cavity oscillator
Regenerative Amplifier FEL

- High Gain Low Feedback concept (Low-Q cavity)

- Los Alamos IR-RAFEL

- TTF VUV-RAFEL

- LCLS X-RAY RAFEL
  Huang Z and Ruth R D 2006 Phys. Rev. Lett. 96 144801

As well as these experiments in the infrared region of the spectrum, this high-gain regime of the FEL oscillator is also of interest in FEL designs for the ultraviolet and higher frequencies. The lack of high mirror reflectivities for these frequencies severely restricts the design of low-gain oscillators.
A design for the generation of temporally-coherent radiation pulses in the VUV and beyond by a self-seeding high-gain free electron laser amplifier

B W J McNeil, N R Thompson, D J Dunning, J G Karssenberg, P J M van der Slot and K-J Boller

Figure 5. A schematic of the 4GLS VUV-FEL with the baseline design parameters. The fundamental cavity mode at $1/e^2$ of the on-axis intensity is shown in blue on the same longitudinal scale as the engineering representation. Electron beam transport is right to left.
Short wavelength regenerative amplifier free electron lasers

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\textsuperscript{b} SUPA, University of Strathclyde, Glasgow G4 0NG, UK

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Fig_1.png}
\caption{Schematic representation of a generic high gain RAFEL system.}
\end{figure}

- Robust FEL cavity design able to generate close to Fourier Transform limited tunable output from feedback factors $F \sim 10^{-5}$: a self-seeding high gain FEL ideal for short wavelength generation
RAFEL *without* MLOK – interesting case of short electron pulse: $l_b \sim l_c$
Parameters are typical for a soft x-ray FEL:

<table>
<thead>
<tr>
<th>Gaussian current electron pulse:</th>
<th>( \sigma_z = l_c ) ( (l_c = \lambda/4\pi\rho) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEL parameter:</td>
<td>( \rho = 2 \times 10^{-3} )</td>
</tr>
<tr>
<td>Undulator length:</td>
<td>( L_u = 6 l_g ) ( (l_g = \lambda_u/4\pi\rho) )</td>
</tr>
<tr>
<td>Cavity feedback factor:</td>
<td>( F = 4 \times 10^{-3} )</td>
</tr>
<tr>
<td>Cavity detuning:</td>
<td>lengthened by ( l_c )</td>
</tr>
</tbody>
</table>

**Fig. 1.** Schematic representation of a generic high gain RAFEL system.
Pass=1
Pass=1

- Top graph: \( |A|^2 \) vs. Optical Intensity
- Middle graph: \( |\chi\rangle \) vs. Beam parameters
- Bottom graph: PSD vs. frequency (f)
Pass=1
Pass=1
\[ |A|^2 \]

Pass=1

Optical Intensity

\[ \chi |b| \]

Beam parameters

PSD
Pass = 1

- \(|A|^2\)
- \(|\chi|\)
- PSD

Graphs showing optical intensity, beam parameters, and PSD.
Pass=1

\[ |A|^2 \]

Optical Intensity

\[ \chi |b| \]

Beam parameters

PSD
Pass=1

$|A|^2$

$|b|$

PSD
Pass=2
Pass=2
Pass=2

|IA|^2

Optical Intensity

\[ \frac{\chi}{|b|} \]

Beam parameters

PSD
Pass=2
Pass=2
Pass=2

\[ |A|^2 \]

Optical Intensity

\[ \chi |b| \]

Beam parameters

\[ PSD \]
Pass=2

|α|^2

Optical Intensity

|χ|b|

Beam parameters

PSD
$|A|^2$

Optical Intensity

$\chi/b$

Beam parameters

PSD
Pass=2

<table>
<thead>
<tr>
<th>A</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Intensity</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>χ/β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam parameters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
</tr>
</tbody>
</table>
Pass=2

\[ |A|^2 \]

Optical Intensity

\[ \chi |l| \]

Beam parameters

\[ PSD \]
And so on until sometime later....
Pass = >> 1
Start wiggler
Pass = \gg 1

End wiggler

This output is stable, with very little temporal jitter or power jitter, pass to pass:

A great candidate for generating single, stable, attosecond pulses in the x-ray.
RAFEL with MLOK –
with short electron pulse: $l_b \sim l_c$
Parameters are typical for a soft x-ray FEL:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian current electron pulse:</td>
<td>$\sigma_z = l_c$</td>
</tr>
<tr>
<td>FEL parameter:</td>
<td>$\rho = 2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Undulator module length X 16:</td>
<td>$L_u = l_g / 4$</td>
</tr>
<tr>
<td>Chicane induced slippage X 16:</td>
<td>$\delta = 1.25 l_c$</td>
</tr>
<tr>
<td>Beam energy modulation amplitude: (can also use current modulation)</td>
<td>$\gamma_{\text{mod}} = \rho \gamma$</td>
</tr>
<tr>
<td>Cavity feedback factor:</td>
<td>$F = 3.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>Cavity detuning:</td>
<td>lengthened by $3 \times l_c$</td>
</tr>
</tbody>
</table>
Pass=1
Module 0
Pass=1
Module 1
Pass=1
Module 5
Pass=1
Module 6
Pass=1
Module 7
Pass=1
Module 10

\[ |A|^2 \]

Optical Intensity

\[ |\chi| \]

Beam parameters

\[ \text{PSD} \]

\[ f \]
Pass=1
Module 12

\begin{align*}
|A|^2 & \\
\chi |b| & \\
\text{PSD} &
\end{align*}
Pass=1
Module 14
Pass=1
Module 15

\[ |A|^2 \]

Optical Intensity

\[ \chi/|b| \]

Beam parameters

PSD

frequency
Pass=1
Module 16
Pass=2
Module 0
Pass=2
Module 1

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A</td>
<td>^2$</td>
</tr>
<tr>
<td>$</td>
<td>b</td>
<td>$</td>
</tr>
<tr>
<td>PSD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pass=2
Module 2
And so on until sometime later....
Pass >>1
Module 0
Pass $\gg 1$

Module 1
Pass >>1
Module 2
Pass >>1
Module 5

\[ |A|^2 \]

\[ \chi |b| \]

\[ \text{PSD} \]
Pass >>1
Module 6
Pass >>1
Module 8
Pass $>>1$

Module 10
Pass >>1
Module 13
Pass >>1
Module 14
Pass >>1
Module 15
Pass >>1
Module 16

Graphs showing various parameters such as optical intensity, beam parameters, and PSD (Power Spectral Density).
Pass >>1 + 1
Module 0
ALICE IR-FEL
J.A. Clarke et al. - MOPA08

Table 1: Nominal ALICE Electron Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Operational Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>35 MeV</td>
<td></td>
</tr>
<tr>
<td>Bunch charge</td>
<td>80 pC</td>
<td></td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>10 mm-mrad</td>
<td></td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>0.6 ps</td>
<td></td>
</tr>
<tr>
<td>Energy spread (rms)</td>
<td>0.1%</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comparison of the ALICE FEL design parameters and those used during recent commissioning.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value</th>
<th>Operational Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>35.0</td>
<td>27.5</td>
</tr>
<tr>
<td>Bunch Charge (pC)</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Normalised Emittance (mm-mrad)</td>
<td>10</td>
<td>-12</td>
</tr>
<tr>
<td>Bunch Length, FWHM (ps)</td>
<td>1.4</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Energy Spread, FWHM (%)</td>
<td>0.25</td>
<td>~0.7</td>
</tr>
<tr>
<td>Max. Train Length (μs)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Bunch Repetition Rate (MHz)</td>
<td>81.25</td>
<td>81.25</td>
</tr>
<tr>
<td>Max Number of Bunches per Train</td>
<td>8125</td>
<td>8125</td>
</tr>
<tr>
<td>Cavity Length (m)</td>
<td>9.224</td>
<td>9.224</td>
</tr>
<tr>
<td>Cavity Mirror ROC (m)</td>
<td>4.75</td>
<td>5.04±0.25</td>
</tr>
<tr>
<td>Single Pass Gain (%)</td>
<td>83</td>
<td>18</td>
</tr>
</tbody>
</table>
### ALICE MLOK IR-FEL
scaled parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian current electron pulse:</td>
<td>$\sigma_z = 2.37 , l_c$</td>
</tr>
<tr>
<td>FEL parameter:</td>
<td>$\rho = 2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Undulator module length X 10:</td>
<td>$L_u = 0.22 , l_g$</td>
</tr>
<tr>
<td>Chicane induced slippage X 10:</td>
<td>$\delta = 0.88 , l_c$</td>
</tr>
<tr>
<td>Beam energy modulation amplitude:</td>
<td>$\gamma_{\text{mod}} = \rho \gamma$</td>
</tr>
<tr>
<td>(can also use current modulation)</td>
<td></td>
</tr>
<tr>
<td>Cavity feedback factor:</td>
<td>$F = 0.9$</td>
</tr>
<tr>
<td>Cavity detuning:</td>
<td>lengthened by $\sim 5 \times l_c$</td>
</tr>
</tbody>
</table>
ALICE MLOK IR-FEL – not really optimised yet

- 80pC, 35MeV, 1ps rms electron bunch.
- Resonant at 4.3µm.
- ALICE FEL undulator rebuilt as ten 4-period sections with integrated delay/matching sections between
- 150kV electron beam energy modulation and ~165µm period.
- Gives 3MW 100fs (FWHM) spikes (7-cycle)

Currently investigating if such an experiment is feasible and fundable.
Conclusions

- Simulations of Mode Locked Optical Klystron configuration predict pulse trains/multi-frequency mode output in both amplifier and cavity resonator FELs.
- RAFEL with short electron pulses gives stable, coherent output of ‘single’ attosecond pulses in x-ray – will investigate how low feedback factor can be ($F \leq 10^{-5}$)?
- RAFEL in MLOK configuration gives APT output.
- Simulations of low gain IR-FEL oscillator in MLOK configuration also predict mode locking.
- Investigating a possible proof-of-principle experiment on the ALICE IR-FEL.
Thank you for listening.