Improving temporal coherence and generating shorter pulses in the FEL

David Dunning & Neil Thompson
Outline

- Harmonic Lasing
- RAFEL
- Mode-locking amplifiers & oscillators for short pulse generation
- EEHG – another look at what can be done
- High Brightness SASE
- Puffin: A three dimensional, unaveraged free electron laser simulation code
- CLARA – a new UK test facility?
Harmonic Lasing
A relative phase change between electrons and fundamental radiation of $n2\pi/3$ ($n$ - integer) will disrupt the fundamental-electron coupling and so the fundamental’s growth.

However, a $n2\pi/3$ phase change for the fundamental is a $n2\pi$ phase change for the 3rd harmonic—The 3rd harmonic interaction therefore suffers no disruption.

*McNeil, Robb & Poole, PAC 2005, Knoxville, Tennessee, 1718-20
Using a seeded steady-state model* (i.e. no pulses effects):

FIG. 2. Scaled powers of fundamental $|A_1|^2$ (solid line) and third harmonic $|A_3|^2$ (dotted line) for wiggler parameter $a_1 = 4$ demonstrating the effects of relative phase changes of $\Delta \theta = 2\pi/3$ at $\bar{z} = 4, 5, 6, \ldots, 24$. For the wiggler parameter retuned to $a_3 = 2.16$, $A_3$ is the fundamental and a separate simulation shows how $|A_3|^2$ (dashed line) evolves.

*McNeil, Robb, Poole & Thompson, PRL 96, 084801 (2006)
Harmonic amplifier SASE optimisation simulations at LCLS and XFEL*

FIG. 7. Averaged peak power for the fundamental harmonic (solid) and the third harmonic (dash) versus geometrical length of the LCLS undulator (including breaks). The wavelength of the third harmonic is 0.5 Å (photon energy 25 keV). Beam and undulator parameters are in the text. The fundamental is disrupted with the help of the spectral filter (see the text) and of the phase shifters. The phase shifts are $4\pi/3$ after segments 1–5 and 17–22, and $2\pi/3$ after segments 6–10 and 23–28. Simulations were performed with the code FAST.

*Schneidmiller & Yurkov, PRST-AB 15, 080702 (2012)

FIG. 8. An example for the European XFEL. Averaged peak power for the fundamental harmonic (solid) and the third harmonic (dash) versus magnetic length of SASE1 undulator. The wavelength of the third harmonic is 0.2 Å (photon energy 62 keV). The fundamental is disrupted with the help of phase shifters installed after 5 m long undulator segments. The phase shifts are $4\pi/3$ after segments 1–8 and 21–26, and $2\pi/3$ after segments 9–16. Simulations were performed with the code FAST.

Could be combined with a self-seeding method at fundamental.
Also works in FEL cavity oscillators for low gain*

\[ |A|^2 \]

Such solutions are ‘generic’ and apply across all wavelength ranges from IR to X-ray (XFELO)


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron pulse charge $Q$</td>
<td>80 pC</td>
</tr>
<tr>
<td>Pierce parameter $\rho$</td>
<td>$2.52 \times 10^{-3}$</td>
</tr>
<tr>
<td>Wiggler parameter $a_w$</td>
<td>4.0</td>
</tr>
<tr>
<td>Feedback factor $F$</td>
<td>0.99</td>
</tr>
<tr>
<td>Cavity detuning $\delta_c$</td>
<td>0.00 $l_c$</td>
</tr>
<tr>
<td>No. of wiggler periods $N_w$</td>
<td>40</td>
</tr>
<tr>
<td>Wiggler length $l_w$</td>
<td>1.27 $l_g$</td>
</tr>
<tr>
<td>No. of phase shifts $N_{\Delta \theta}$</td>
<td>19</td>
</tr>
<tr>
<td>Size of phase shifts $\Delta \theta$</td>
<td>$2\pi/3$</td>
</tr>
</tbody>
</table>

Table 5.2: Parameters used in the proof of concept test.
...and in FEL cavity oscillators in the high gain (RAFEL)*

Such solutions are ‘generic’ and apply across all wavelength ranges from IR to X-ray (XFELO)

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
UK RAFEL in 4GLS

Table 1. Predicted VUV-FEL radiation output.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning range</td>
<td>$\sim 3\text{–}10 \text{ eV}$</td>
</tr>
<tr>
<td>Peak power</td>
<td>$\sim 500\text{–}300 \text{ MW (3 GW)}$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$n \times 4\frac{1}{3} \text{ MHz (}n \leq 300, \text{ integer)}$</td>
</tr>
<tr>
<td>Polarization</td>
<td>Variable elliptical</td>
</tr>
<tr>
<td>Min pulse duration FWHM</td>
<td>170 fs (25 fs)</td>
</tr>
<tr>
<td>Typical $\Delta \nu \Delta t$</td>
<td>$\sim 1.0$</td>
</tr>
<tr>
<td>Maximum pulse energy</td>
<td>70 $\mu$J</td>
</tr>
<tr>
<td>Maximum average power</td>
<td>$n \times 300 \text{ W}$</td>
</tr>
</tbody>
</table>

*a*Indicates possible output in superradiant mode of operation.


*McNeil, Thompson, Dunning, Karssenberg, van der Slot & Boller, New Journal of Physics 9 239 (2007)*
WHY A RAFEL?*

- Robust FEL cavity design able to generate close to Fourier Transform limited tuneable output from feedback factors $F \times 10^{-5}$: a self-seeding high gain FEL ideal for short wavelength generation

*Dunning, McNeil & Thompson, NIM A 593, 116-9 (2008)
Example short-pulse RAFEL simulation

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 length:</td>
<td>$L_u = 6 l_g$</td>
</tr>
<tr>
<td>Cavity feedback factor:</td>
<td>$F = 4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Cavity detuning:</td>
<td>shortened by $2l_c$</td>
</tr>
</tbody>
</table>

Short pulse RAFEL – stable, coherent output

Figure 1: Short pulse RAFEL simulation - showing saturated evolution at the undulator entrance. From top: scaled power at the beginning of the interaction at saturation; the current-weighted bunching; the scaled spectral power as a function of scaled frequency.

Figure 2: Short pulse RAFEL simulation - showing saturated evolution at the undulator exit.

Short (< \( l_0 \)), high power, FT limited pulses with none of the jitter associated with SASE.

Mode-locking amplifiers & oscillators for short pulse generation
Axial Modes from an *amplifier* FEL

- Synthesise axial mode spectrum without cavity

Electron delay $\delta^*$

$N_w$ period undulator

Slippage $\bar{l}$

Total shift $\bar{s} = \delta + \bar{l}$

Electron delay $\delta$

$N_w = 1$

$\omega_{n=1}$

$\omega_{n=2}$

$\omega_{n=3}$

$s = \frac{\lambda}{\pi}$

$e$

*Jones, Clarke & Thompson, IPAC 2012, USA, 1759 (2012). (For ‘dispersionless’ chicanes)*
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 $\lambda_j$:

\[ s = N\lambda_j = (N + 1)\lambda_{j-1} \]

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

Electron energy modulation at mode spacing

*Thompson, McNeil, PRL 100, 203901 (2008)
MLOK with current modulation*

Amplified HHG – retaining structure with MLOK*

Amplified HHG – retaining structure with MLOK

Fig. 7: Longitudinal intensity profile (top) and spectral power distribution (bottom) of the HH seed in 3D simulations.

3D Genesis simulations for $\lambda_r \approx 12$ nm

Fig. 8: Longitudinal intensity profile (top and middle) and spectral power distribution (bottom) of the amplified HH radiation in 3D simulations, with $S_e = 8$. The agreement with the equivalent 1D simulations shown in Fig. 6 is very good.
Start-to-end simulations*

Input for NLS – like parameters

*Dunning, McNeil, Thompson, Williams, Phys. Plasmas 18, 073104 (2011)
Start-to-end simulations - output
RAFEL in MLOK configuration*

Fig. 3: Short-pulse MLOK RAFEL simulation — showing saturated evolution at the undulator entrance. From top: scaled power at the beginning of the interaction at saturation; the current-weighted bunching; the scaled spectral power as a function of scaled frequency.


Fig. 4: Short-pulse MLOK RAFEL simulation — showing saturated evolution at the undulator exit.
Mode Locked After Burner*

### TABLE I: Parameters for soft and hard x-ray simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soft x-ray</th>
<th>Hard x-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplifier stage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron beam energy [GeV]</td>
<td>2.25</td>
<td>8.5</td>
</tr>
<tr>
<td>Peak current [kA]</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>$\rho$-parameter</td>
<td>$1.6\times10^{-3}$</td>
<td>$6\times10^{-4}$</td>
</tr>
<tr>
<td>Normalised emittance [mm-mrad]</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>RMS energy spread, $\sigma_\gamma/\gamma_0$</td>
<td>0.007 %</td>
<td>0.006 %</td>
</tr>
<tr>
<td>Undulator period, $\lambda_u$ [cm]</td>
<td>3.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Undulator periods per module</td>
<td>78</td>
<td>277</td>
</tr>
<tr>
<td>Resonant wavelength, $\lambda_r$ [nm]</td>
<td>1.24</td>
<td>0.1</td>
</tr>
<tr>
<td>Modulation period, $\lambda_m$ [nm]</td>
<td>38.44</td>
<td>3</td>
</tr>
<tr>
<td>Modulation amplitude, $\gamma_m/\gamma_0$</td>
<td>0.1 %</td>
<td>0.06 %</td>
</tr>
<tr>
<td>Extraction point [m]</td>
<td>34.1</td>
<td>36.0</td>
</tr>
<tr>
<td><strong>Mode-locked afterburner</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Undulator periods per module</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Chicane delays [nm]</td>
<td>28.52</td>
<td>2.2</td>
</tr>
<tr>
<td>No. of undulator-chicane modules</td>
<td>$\sim15$</td>
<td>$\sim40$</td>
</tr>
</tbody>
</table>

Optimum for: \( \gamma_m/\gamma_0 \approx \rho \)
Soft X-ray Genesis simulation

FIG. 3: Soft x-ray mode-locked afterburner simulation results: Radiation power profile and spectrum after (a) 2, (b) 5 and (c) 15 undulator-chicane modules. The duration of an individual pulse after 15 modules is $\sim 9$ as rms.
Hard X-ray Genesis simulation

A (fantasy?) projection of these results to the LANL MaRIE proposal* for $\lambda_r \approx 0.25\ \text{Å}$ (50 keV photons) gives RMS pulse durations of 140 zs. These parameters allow us to consider experiments involving observation of electronic/nuclear and towards nuclear behaviour.

EEHG – another look at what can be done
EEHG mechanism*

*Stupakov, Phys. Rev. Lett. 102, 074801 (2009)
EEHG without periodic BC’s or averaging*

*Henderson, McNeil, ‘Echo enabled harmonic generation free electron laser in a mode-locked configuration’, to be published in EPL
Normal radiator undulator

\[ \lambda_r \approx 10 \text{ nm} \]

Fig. 5: Electron and radiation pulse at saturation in a simple undulator at \( \bar{z} \approx 1.1 \) for the normal EEHG case. Plots on the left are: top - normalised electron number histogram (bin size \( = \lambda_r / 5 \)); bottom - Fourier transform of bunching \( b(\bar{z}, \bar{\omega}) \). On the right: top - radiation field amplitude \( |A|^2 \) as a function of \( \bar{z}_1 \); bottom - scaled Power Spectral Density showing emission at resonance dominates.
The visibility of radiation pulse train structure is defined as 
\[ V = \frac{|A|_{max}^2 - |A|_{min}^2}{(|A|_{max}^2 + |A|_{min}^2)} \]
were the maximum and minimum values are defined between two adjacent peaks. The effect of introducing an energy spread \( \sigma_E \) in the initial electron pulse energy decreases the visibility gradually from \( V = 0.93 \) at 1 keV \( (\sigma_E/\rho E_r = 0.0008) \) to \( V = 0.78 \) at 150 keV \( (\sigma_E/\rho E_r = 0.125) \).
High Brightness SASE
HB-SASE
Mode Locked Optical Klystron undulator/chicane structure, but with different chicane delays*

Each chicane now introduces **different** integer resonant wavelength delay to e⁻

![Diagram of Mode Locked Optical Klystron undulator/chicane structure]

- Only central (resonant) mode remains after many undulator/chicane modules
- For undulator lengths \(< l_g\) the coherence length changes from the SASE value of \(\sim l_c\) to the total relative electron/radiation slippage length \(>> l_c\)
- **The localised collective interaction between radiation & electrons has been broken**

*Thompson, Dunning & McNeil, ‘*Improved temporal coherence in SASE FELs*, TUPE050, Proceedings of IPAC’10, Kyoto, Japan
HB-SASE average power
HB-SASE Spectrum for simulation in soft X-ray at 1.24 nm*

The system of shifts acts like a ‘distributed monochronometer’.

SASE & HB-SASE comparison*

Puffin: A three dimensional, unaveraged free electron laser simulation code

(Parallel Unaveraged Fel INtegrator)
Puffin: A three dimensional, unaveraged free electron laser simulation code

L. T. Campbell\textsuperscript{1,2,a}) and B. W. J. McNeil\textsuperscript{1,b)}

\textsuperscript{1}University of Strathclyde (SUPA), Glasgow G4 0NG, United Kingdom
\textsuperscript{2}ASTeC, STFC Daresbury Laboratory and Cockcroft Institute, Warrington WA4 4AD, United Kingdom

FIG. 4. Left: Spectrum of the $y$-polarised field. The blue line shows the field at $\bar{x}, \bar{y} = 0$, and the red line is the field at point $\bar{x} = 0, \bar{y} = 0.3796$. Note the even harmonics are only present off-axis. Right: The phase-front of the $y$-polarised field of the second harmonic at a transverse slice in $\bar{z}_2$ exhibits the expected transverse modal structure.
Non-localised electron evolution & very short pulses*

Figure 4: The transverse intensity profile near the peak at $\bar{z} = 7.6676$ and $\bar{z}_2 = 7.0456$ as shown in Fig. 5.

Figure 5: The scaled power $|A|^2$ is calculated by integrating the scaled intensity of Fig. 4 over the transverse area and is plotted as a function of $\bar{z}_2$ for $\bar{z} = 7.6676$.

Figure 6: The spectral intensity calculated on-axis along the $\bar{z}_2$ axis at $\bar{z} = 7.6676$. 
CLARA – a new UK test facility?*

[Compact Linear Accelerator for Research and Applications]

* Clarke et al., TUPPP066, Proceedings of IPAC2012, New Orleans, Louisiana, USA Slides courtesy of Jim Clarke, ASTeC.
To develop a normal conducting test accelerator able to generate longitudinally and transversely bright electron bunches and to use these bunches in the experimental production of **stable, synchronised, ultra short** photon pulses of coherent light from a single pass FEL with techniques directly applicable to the future generation of light source facilities.
CLARA Timeline

- Outline Design of CLARA – Dec 2012
- Design Report and Costing – March 2013
- CLARA construction – 2013 to 2015
- CLARA first commissioning – 2016

Funding required!
Thank You!
Feasibility III - Stability

2.1 Energy Spread

High-gain optical klystron theory [1] gives a criterion for operation which relates the electron beam energy spread to the dispersive strength of the chicane:

\[ \bar{\sigma}_\gamma \equiv \frac{\sigma_\gamma}{\rho_\gamma} \lesssim \frac{1}{D}, \]

where \( D = 2\pi \rho_6 / \lambda_r \) and \( R_6 \approx 10\delta / 3 \) is the momentum compaction factor, with \( \delta \) the chicane delay, giving

\[ \sigma_\gamma \lesssim 3\lambda_r \]

Using...

<table>
<thead>
<tr>
<th>( \sigma_\gamma / \gamma )</th>
<th>XUV</th>
<th>X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_\gamma / \gamma &lt; 1/20N_c )</td>
<td>( 1 \times 10^{-3} )</td>
<td>( 2 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \Delta B / B &lt; 1/(2N_c \sqrt{N}) )</td>
<td>( 2 \times 10^{-3} )</td>
<td>( 4 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Table 2: Required tolerances for SASE mode-locking, for the XUV and X-ray cases.

\[ \lambda = \frac{\lambda_w}{2\gamma^2(1 + a_w^2)} \]  

so that the tolerance over \( N \) modules will be reduced by \( 1/\sqrt{N} \) to give

\[ \frac{\Delta B}{B} < \frac{1}{2N_c \sqrt{N}}. \]

where \( \gamma = E / E_0 \) for a relativistic beam, the delay in units of resonant wavelengths is then given by

\[ \frac{\delta}{\lambda} = \frac{2L^3 B^2 c^2}{\lambda_w E_0^2 (1 + a_w^2)}, \]

which is independent of the beam energy so that as the beam energy fluctuates the chicanes always delay by exactly the same number of resonant wavelengths. This means that although the resonant wavelength may vary the development of the axial mode structure is unaffected.

2.2 Magnet Stability

The delay in a 4-dipole chicane with equal magnet and drift lengths, \( L \), may be written as

\[ \delta = L\phi^2 \]

(3)

where \( \phi \) is the deflection angle which is assumed to be small. For a relativistic beam the deflection angle in a single dipole of length \( L \) and field strength \( B \) is

\[ \phi = \frac{B c}{E} \]

where \( E \) is the beam energy in units of \( \text{GeV} \). Therefore from (3)...

2.3 Imaging

The effective instantaneous losses in the synchrotron resonant imaging regime are from beam walk...