Other Uses of ERL based LHeC

1. LHeC-FEL  Zafer Nergiz, Frank Zimmermann, Husnu Aksakal
2. $\gamma\gamma$ Higgs factory SAPPHiRE  Atoosa Meseck, Frank Zimmermann

“Electrons for the LHC” workshop,
LAL Orsay, 28 June 2018
LHeC recirculating linac reconfigured for FEL operation
The main LHeC-ERL electron beam parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>GeV</td>
<td>40.0</td>
</tr>
<tr>
<td>relativistic gamma</td>
<td></td>
<td>78277.9</td>
</tr>
<tr>
<td>electrons per bunch</td>
<td></td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\mu$m</td>
<td>7</td>
</tr>
<tr>
<td>peak beam current</td>
<td>kA</td>
<td>8.2</td>
</tr>
<tr>
<td>average beam current</td>
<td>mA</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td>normalized emittance</td>
<td>$\mu$m</td>
<td>0.5</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>ns</td>
<td>25</td>
</tr>
<tr>
<td>rms energy spread</td>
<td>%</td>
<td>0.1</td>
</tr>
</tbody>
</table>

optimum match: $\varepsilon_N \leq \frac{\gamma \lambda}{4\pi}$ ✓ OK for sub-Angstrom wavelengths
LHeC-FEL goal: hard X-ray FEL radiation in the range between 0.45 Å and 2.2 Å

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [MeV]</td>
<td>20</td>
<td>17</td>
<td>120</td>
</tr>
<tr>
<td>peak current [A]</td>
<td>3000</td>
<td>35</td>
<td>300</td>
</tr>
<tr>
<td>average current [mA]</td>
<td>100</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>photon wavelength [μm]</td>
<td>40</td>
<td>22</td>
<td>1.6</td>
</tr>
<tr>
<td>average FEL power [W]</td>
<td>500</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>pulse duration [ps]</td>
<td>50</td>
<td>0.32</td>
<td>0.17</td>
</tr>
</tbody>
</table>
LHeC FEL wavelength (contours) as a function of electron beam energy (vertical axis) and undulator parameter (horizontal axis).

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ K = 0.934 \, B \, [T] \lambda_u \, [cm] \]
$\lambda_u = 5.5$ cm

Magnet arrays of undulator. Permanent magnet elements are in blue and the iron poles in red. All units are in mm. Only first few periods shown.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>period length (cm)</td>
<td>5.5</td>
</tr>
<tr>
<td>number of period</td>
<td>61</td>
</tr>
<tr>
<td>total length (m)</td>
<td>120</td>
</tr>
<tr>
<td>minimum gap (mm)</td>
<td>7.2</td>
</tr>
<tr>
<td>“undulator parameter” $K$</td>
<td>4.2–9.9</td>
</tr>
<tr>
<td>wavelength range (Å)</td>
<td>0.45–2.24</td>
</tr>
</tbody>
</table>

Vertical magnetic field along the axis of the U55 undulator for a gap of 12.4 mm; only a few periods shown.
evolution of the pulse power along the undulator

spatial (temporal) profile of the radiation pulse

wavelength spectrum of the radiation

### Genesis simulation results

for $\lambda=0.45$ Å ($K = 4.24$)

for $\lambda=1$ Å ($K = 6.5$)

for $\lambda=2.24$ Å ($K = 9.9$)
LHeC-FEL radiation parameters derived from simulations. The peak-power values were obtained by averaging the simulated power over the length of the pulse ($\pm \sigma_z$). The unit for the corresponding peak and average brilliance ($B$) is equal to photons/mm$^2$/mrad$^2$/s/0.1%bw.

<table>
<thead>
<tr>
<th>parameters</th>
<th>Unit</th>
<th>K=4.24</th>
<th>6.5</th>
<th>9.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron energy</td>
<td>GeV</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>wavelength</td>
<td>nm</td>
<td>0.045</td>
<td>0.1</td>
<td>0.225</td>
</tr>
<tr>
<td>photon energy</td>
<td>keV</td>
<td>27.7</td>
<td>12.41</td>
<td>5.54</td>
</tr>
<tr>
<td>saturation length</td>
<td>m</td>
<td>110</td>
<td>85</td>
<td>70</td>
</tr>
<tr>
<td>peak power</td>
<td>GW</td>
<td>40</td>
<td>65</td>
<td>120</td>
</tr>
<tr>
<td>pulse duration</td>
<td>fs</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>bandwidth</td>
<td>%</td>
<td>0.04</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>photons per pulse</td>
<td>#</td>
<td>$5.2\times10^{11}$</td>
<td>$2.5\times10^{12}$</td>
<td>$7.8\times10^{12}$</td>
</tr>
<tr>
<td>peak brilliance</td>
<td>B</td>
<td>$4.5\times10^{34}$</td>
<td>$2.6\times10^{34}$</td>
<td>$1.2\times10^{34}$</td>
</tr>
<tr>
<td>average brilliance</td>
<td>B</td>
<td>$1.0\times10^{29}$</td>
<td>$6.0\times10^{28}$</td>
<td>$2.8\times10^{28}$</td>
</tr>
</tbody>
</table>
peak brilliance, LHeC-FEL compared with state-of-the-art

- LHeC-FEL at CERN?
- European XFEL at DESY
- LCLS-II at SLAC
- SwissFEL at PSI

LHeC-FEL proposed by H. Schopper at the start of 2017 LHeC workshop; Z. Nergiz, F. Zimmermann, H. Aksakal, first results during WS, draft report
highlight ARIES WP6.5 workshop \(LHeC/FCC-eh\)
average brilliance, \(LHeC-FEL\) compared with state-of-the-art

\[ \text{Average Brilliancy (Photons/s/mm}^2\text{mrad}^2\text{/0.1\%BW)} \]

- **LHeC-FEL proposed by H. Schopper at the start of 2017 LHeC workshop;**
  - Z. Nergiz, F. Zimmermann,
  - H. Aksakal, first results during WS, draft report

- **3x10^3**

- **x3**

- **LCLS-II at SLAC**

- **European XFEL at DESY**

**LHeC-FEL at CERN?**
evolution of the electron energy loss in units of gamma along the undulator region

loss of ~3.9 MeV (<<500 MeV)

→ no problem for energy recovery

evolution of the electron beam energy spread in units of the electron rest mass energy along the undulator region

increase from ~0.1 to ~0.4%
LHeC-FEL Conclusions

• 40 GeV LHeC can produce SASE FEL radiation in (sub-) Angstrom wavelength regime at exceedingly high peak power and brilliance

• both peak and average brilliance far exceed other, existing or proposed X-ray FELs; e.g. at $\lambda=0.45$ Å, peak power 120 GW, peak brilliance $4.5\times10^{34}$ photons/mm$^2$/mrad$^2$/s/0.1%bw

• beam is cw with 25 ns bunch spacing, translating into a remarkable average brilliance

• self seeding and tapered undulator would yield even better performance
References for LHeC –FEL

SAPPHiRE++
Photon Beams, Padua
27-28 November 2017

state-of-the-art in $\gamma\gamma$ colliders, Compton sources, $\gamma$ factories
a new type of collider

γ γ collider Higgs factory

s-channel production;
lower energy;
no $e^+e^-$ source

another advantage:
no beamstrahlung
→ higher energy reach
than $e^+e^-$ colliders
\( \gamma \gamma \) collider based on \( e^- \)

combining photon science & particle physics!

K.-J. Kim et al.
Higgs $\gamma\gamma$ production cross section


Left: The cross sections for $\gamma\gamma \rightarrow h$ vs $M_h$ as functions of $E_{cm}(e^-e^-)$.

Right: The cross section for $\gamma\gamma \rightarrow h$ vs $M_h$ for three different values of $E_{cm}(e^-e^-)$.

Assumptions: $e^-$ have 80% longitudinal polarization and lasers are circularly polarized, so that produced photons are highly circularly polarized at their maximum energy.
which beam & photon energy / wavelength?

\[ E_{\gamma,\text{max}} = \frac{x}{1 + x} E_{\text{beam}} \]

\[ x = \frac{4E_e\omega_L}{m_e^2} \cos^2 \frac{\theta}{2} \]

example \( x \approx 4.3 \) (for \( x > 4.83 \): coherent pair production)

with \( E_{\text{beam}} \approx 80 \text{ GeV} \): \( E_{\gamma,\text{max}} \approx 66 \text{ GeV}, E_{\text{CM, max}} \approx 132 \text{ GeV} \)

\( E_{\text{photon}} \approx 3.53 \text{ eV}, \lambda \approx 351 \text{ nm} \)
Reconfiguring \( LHeC \rightarrow SAPPHiRE \)

**SAPPHiRE**

\[ \gamma\gamma \text{Higgs factory} \]

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*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons*
SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

doubling the number of arcs + electrostatic separators

scale ~ European XFEL, about 10-20k Higgs per year

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons
<table>
<thead>
<tr>
<th>SAPPHiRE</th>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total electric power</td>
<td>$P$</td>
<td>100 MW</td>
</tr>
<tr>
<td>beam energy</td>
<td>$E$</td>
<td>80 GeV</td>
</tr>
<tr>
<td>beam polarization</td>
<td>$P_e$</td>
<td>0.80</td>
</tr>
<tr>
<td>bunch population</td>
<td>$N_b$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>repetition rate</td>
<td>$f_{rep}$</td>
<td>200 kHz</td>
</tr>
<tr>
<td>bunch length</td>
<td>$s_z$</td>
<td>30 μm</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\theta_c$</td>
<td>≥20 mrad</td>
</tr>
<tr>
<td>normalized horizontal/vert. emittance</td>
<td>$\gamma\epsilon_{x,y}$</td>
<td>5,0.5 μm</td>
</tr>
<tr>
<td>horizontal IP beta function</td>
<td>$\beta_x^*$</td>
<td>5 mm</td>
</tr>
<tr>
<td>vertical IP beta function</td>
<td>$\beta_y^*$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>horizontal rms IP spot size</td>
<td>$\sigma_x^*$</td>
<td>400 nm</td>
</tr>
<tr>
<td>vertical rms IP spot size</td>
<td>$\sigma_y^*$</td>
<td>18 nm</td>
</tr>
<tr>
<td>horizontal rms CP spot size</td>
<td>$\sigma_x^{CP}$</td>
<td>400 nm</td>
</tr>
<tr>
<td>vertical rms CP spot size</td>
<td>$\sigma_y^{CP}$</td>
<td>440 nm</td>
</tr>
<tr>
<td>e⁻e⁻ geometric luminosity</td>
<td>$L_{ee}$</td>
<td>$2\times10^{34}$ cm⁻²s⁻¹</td>
</tr>
</tbody>
</table>
SAPPHiRE $\gamma\gamma$ luminosity

luminosity spectra for SAPPHiRE as functions of $E_{CM}(\gamma\gamma)$, computed using Guinea-Pig for three possible normalized distances $\rho \equiv l_{CP/IP}/(\gamma\sigma_y^*)$ (left) and different polarizations of in-coming particles (right)

$\rho = 1 \leftrightarrow l_{CP/IP} \sim 2$ mm
improving the SAPPHiRE $\gamma \gamma$ Higgs factory

2017 innovations (A. Meseck/ HZB):

- beam circulating only in one direction - applicable to both laser and FEL schemes
- refined FEL scheme driven by separate low-energy beams

Generic recirculator-based $\gamma \gamma$ Higgs factory with two FELs (A. Meseck).

- Simple Scheme!
- Each FEL-Line delivers more than $10^{16}$ photons per pulse.
- Strongly focussed beams for inverse compton scattering mandatory! Transverse radiation and beam sizes about 300nm!
- Focussing of FEL-radiation and electron beam challenging!
- Kicker system needs detailed studies!

seeding and frequency upconversion possible
required number of 3.5 eV photons per bunch as a function the beam dimension at the collision point for different gamma yields

using formula from PhD thesis of C. Curatolo (2016)
SAPPHIRE R&D items

- $\gamma\gamma$ interaction region & spent e-
- large high-finesse optical cavity & high repetition rate laser
  - or *FEL implementation*
- *fast kicker*
  - or separation scheme for beams circulating in opposite directions
- polarized low-emittance e\(^{-}\) gun
- separation of spent beam after conversion
SAPPHiRE Conclusions

• SAPPHiRE = one of the cheapest possible options to further study the Higgs; a serendipitous additional use of the LHeC RLA!

• a refined scheme with fast kicker and bypass avoids beam circulating in opposite direction and reduces the number of return loops by factor 2

• specific laser + optical cavity system meeting the requirements to be developed

• alternative attractive FEL option
References for LHeC and SAPPHiRE:

[8] A. Meseck, numerous private communications