Light sources based on optical-scale accelerators

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Input from...
Claudio Pellegrini, Sven Reiche, Chris Seers, Chris McGuinness, Eric Colby, Joel England, Josh McNeur

Material stolen from... lots of people including C. Brau, J. Jarvis, T. Plettner
I want to thank the organizers for the opportunity

Eric

Bruce

Me

< 10 days

talk length = f(t)

Make a light source!

non-functional technology
Can you build an iPad sized light source?
Should you build it?
Optical-scale dielectric-structures promise GeV/m gradients and naturally short bunches

+ very short pulses
+ very high repetition rate
+/- low charge
- no track record
- limited R&D work

! The red-headed stepchild of AA

Tolerances:
PWFA: ~300nm
LWFA: ~30nm
MAP: ~10nm

Gradients x10-x100 metal
Structural control of fields
Many possible geometries
Scalable fabrication
Basically, an FEL or ICS source has an injector, accelerator, radiator, and x-ray beamline.

\[ \rho = \frac{1}{2\gamma} \left( \frac{\lambda_u f_c a_w}{2\pi} \right)^2 \frac{I}{I_A \sigma_x \sigma_y} \right]^{\frac{1}{3}} \]

\[ L_g = \frac{\lambda_u}{4\sqrt{3}\pi \rho} \]

\[ P_{sat} = 1.6 \rho P_{beam} = 1.6 \frac{mc^2}{e} \rho \gamma I \]

\[ \frac{\sigma_x}{\gamma} \ll \rho \]

\[ k_p = \sqrt{\frac{4\pi I}{\gamma A A}} \ll 2k_u \rho \gamma \]
The choice of accelerator technology impacts the possible light source configurations...

<table>
<thead>
<tr>
<th></th>
<th>RF</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>10-100 MeV/m</td>
<td>1-10 GeV/m</td>
</tr>
<tr>
<td>Energy gain per period</td>
<td>1 MeV</td>
<td>1 keV</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>100 Hz</td>
<td>10-100 MHz</td>
</tr>
<tr>
<td>Charge per Bunch</td>
<td>0.1 - 1+ nC</td>
<td>0.01-1 pC</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>1-100 ps</td>
<td>1-100 fs</td>
</tr>
</tbody>
</table>

**key:** charge and time scale; not gradient
... the undulator technology has at least as much impact on the FEL design.

<table>
<thead>
<tr>
<th>PM</th>
<th>Micro/Pulsed</th>
<th>RF</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>&gt;1 cm</td>
<td>0.1 - 1 mm</td>
<td>0.1-1 cm</td>
</tr>
<tr>
<td>Parameter</td>
<td>1-10</td>
<td>&lt;1</td>
<td>~1</td>
</tr>
<tr>
<td>Gap</td>
<td>5 mm</td>
<td>1 mm</td>
<td>1+ cm</td>
</tr>
<tr>
<td>Status</td>
<td>Mature</td>
<td>some SC work</td>
<td>stalled</td>
</tr>
</tbody>
</table>

Focusing is an addition issue:

\[ \beta_{opt} \approx 3 \sqrt{\frac{\varepsilon_n}{\gamma}} \frac{4\pi}{\lambda} L_g \]
An example of a soft x-ray FEL-based source reveals the need for new undulator approaches.

<table>
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<tbody>
<tr>
<td>Wavelength</td>
<td>6 nm</td>
</tr>
<tr>
<td>Beam energy</td>
<td>25.5 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Emittance (norm.)</td>
<td>0.06 µm (doh!)</td>
</tr>
<tr>
<td>Charge</td>
<td>1 pC (whew!)</td>
</tr>
<tr>
<td>Peak current</td>
<td>750 A</td>
</tr>
<tr>
<td>Undulator parameter</td>
<td>1</td>
</tr>
<tr>
<td>Undulator period</td>
<td>20 µm</td>
</tr>
<tr>
<td>Focusing betafunction</td>
<td>~ 3 mm</td>
</tr>
<tr>
<td>Gain length</td>
<td>500 µm</td>
</tr>
<tr>
<td>FEL parameter</td>
<td>~$3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Saturation length</td>
<td>6 mm (LOL)</td>
</tr>
<tr>
<td>x-ray flux per bunch</td>
<td>~$5 \times 10^8$</td>
</tr>
</tbody>
</table>

$10^6$ electrons; $10^8$ photons

$L_{coop}/\sigma_L<1$: 1-2 spikes

Pellegrini and Travish
A laser undulator for the 20µm case requires guiding or LLNL class lasers

<table>
<thead>
<tr>
<th>Magic 20µm laser (similar for 10µm case)</th>
<th>Beating lasers 800 nm + 1µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>for $a_u=1$ need</td>
<td>for $a_u=1$ need</td>
</tr>
<tr>
<td>$E_L = 35 J$</td>
<td>$E_L = 8 J \times 2$</td>
</tr>
<tr>
<td>$P_L \sim 1$ TW</td>
<td>$P_L &lt; 1$ TW</td>
</tr>
</tbody>
</table>

$$Z_R = \frac{\pi w_0^2}{\lambda_L} \approx 2 L_U = 12$ mm$$

$w_0 \sim 330 \mu$m $\quad w_0 \sim 70 \mu$m

A hard x-ray FEL source using optical period undulator would be too low energy to function well.

An ICS-based hard x-ray source could produce tolerable fluxes if laser guiding works.
We need to develop four critical technologies to make the iPad sized Light Source

1. Ultra low emittance injectors
2. Optical-scale accelerators
3. Micron-period undulators
4. Laser guiding
Low charge, high brightness injectors
Conventional RF photoinjectors are a viable source of low-charge, low-emittance beams

LCLS injector
@ 20 pC
achieved
0.13µm emittance

At ~1 pC, we need <0.01µm (10 nm) emittances

What’s the problem?
- Preservation of nm emittances
- Laser technology (MHz repetition rates)
- Injection into optical structures
Electron microscopes achieve the requisite emittances, albeit at very low current. Field and photo-assisted field emission work well. Needle cathode work is showing the way.
Injection into a sub-micron aperture and a sub-ps bucket is a concern

IFEL

Final focus type
Asymmetric emittances
IFEL pre-bunching
Dielectric Injector

E. Colby

Flat beam


\[ \frac{\varepsilon_y}{\varepsilon_x} \approx 50 \]
Longitudinal manipulation (bunching) of the beam on the attosecond level has been shown.

\[ \Delta \gamma = \frac{\pi NK_xK_w}{\gamma} \frac{\lambda_w}{\lambda_l} \cos(k_i z_0) \]

\[ R_{56} = \frac{L}{\gamma^2} + \left( \frac{q}{\gamma mc} \right)^2 \int_{-\infty}^{\infty} \int B(z') dz' \]

velocity bunching
~5% of total

C. Sears
Integrating the injector and optical scale accelerator may be the best path.
Creating low beta optical-scale structures is hard. Really hard.

John Breuer, Christopher M. S. Sears, Tomas Plettner, and Peter Hommelhoff

100 MeV/m @ 30nm from grating

Low β MAP

<table>
<thead>
<tr>
<th>Color</th>
<th>Height (nm)</th>
<th>Width (nm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>90</td>
<td>120</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Blue</td>
<td>60</td>
<td>120</td>
<td>HfO₂</td>
</tr>
<tr>
<td>Red</td>
<td>240</td>
<td>100</td>
<td>MgF₂</td>
</tr>
<tr>
<td>Green</td>
<td>240</td>
<td>170</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Purple</td>
<td>240</td>
<td>105</td>
<td>HfO₂</td>
</tr>
<tr>
<td>Yellow</td>
<td>240</td>
<td>130</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Blue</td>
<td>240</td>
<td>59</td>
<td>Ge</td>
</tr>
</tbody>
</table>

All dielectric design needs work
Optical-scale accelerator structures
Here at SLAC, the E-163 AARD team is producing a set of laser-driven dielectric micro-accelerators.
PBG-fiber-based structures afford large apertures and scalability to HEP-length structures

X. E. Lin “Photonic bandgap fiber accelerator,” PRSTAB 4, 051301 (2001)

Efficient coupling to the accelerating mode of a PBG fiber is complicated by various issues:
- overmoded: coupling to other modes drains away input power
- extra modes are lossy and difficult to simulate
- initial simulation results from overlap with accelerating mode: ~12%

HFSS: custom dielectric waveguide coupler

~2.5 GV/m
Planar structures offer beam dynamics advantages as well as ease of coupling power.

Flat beam LS: modes? coherence? undulator?
The MAP structure consists of a diffractive optic coupling structure and a partial reflector.
The Micro Accelerator Platform (MAP) is undergoing intense simulation and fabrication study.
We are planning a $\beta=1$ MAP beam de/acceleration experiment here at E163.
The log-pile structure is being fabricated and offers an intermediate gradient solution.

Gradient
221 MeV/m @ 1.55µm

Fabrication
Amenable to higher damage thresholds

C. McGuinness
The Stanford grating structure is non-resonant and might support >10GeV/m

Materials near beam = easy to make the fields; bad for wakefields = 10 fs pulses; but complex coupling and synchronization

Plettner, et al., PAC 2007

Power efficiency improves with decreasing stored energy

\[ P_{ac} \propto \frac{G \lambda^2}{\eta} E_{cm} \]

\[ E_{cm} \propto \left( \frac{\eta P_{ac}}{\lambda^2} \right)^{1/G} \]

SOURCE FLUENCE
These planar structures are modular and scalable

easy power coupling

“easy” to scale & stage

flat beams

low wakefields

>50µm //
Toyota Executive Says Recall Might 'Not Totally' Solve Accelerator Problems

He doesn’t know the half of it!
Example: focusing issues in the MAP

Alternating Phase Focusing

periodically modulating the position of the coupling slot

$$\phi_s = \phi_0 + \phi_m \sin(k_p z)$$

\[
\langle y''_{sec} \rangle = \left\{ \frac{\alpha_r f k_z^2}{\gamma^3 \beta^2} \sin(\phi) \left( 1 - \frac{\phi_m^2}{4} \right) - \frac{\alpha_r f k_z^4 \phi_m^2}{2 \gamma^6 \beta^4 k_p^2} \cos^2(\phi) \right\} \langle y_{sec} \rangle
\]

\[
\langle \phi'' \rangle = \frac{\alpha_r f^2 k_z^4 \phi_m^2}{2 \gamma^6 \beta^4 k_p^2} \cos(\phi) [\sin(\phi) - \sin(\phi)] + \frac{\alpha_r f k_z^2}{\gamma^3 \beta^2} [\cos(\phi) - \cos(\phi_0)]
\]

Initial analysis

bucket depth is impossibly limited

<table>
<thead>
<tr>
<th>$\phi_m$ (radians)</th>
<th>$\frac{k_p}{k_z}$</th>
<th>Long. Acceptance (radians)</th>
<th>Bucket Depth (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.785</td>
<td>.035</td>
<td>.667</td>
<td>6.15</td>
</tr>
<tr>
<td>.785</td>
<td>.03</td>
<td>.8</td>
<td>11.5</td>
</tr>
<tr>
<td>.785</td>
<td>.025</td>
<td>.94</td>
<td>22.1</td>
</tr>
<tr>
<td>.785</td>
<td>.02</td>
<td>1.1</td>
<td>44.1</td>
</tr>
<tr>
<td>.75</td>
<td>.035</td>
<td>.68</td>
<td>6.7</td>
</tr>
<tr>
<td>.8</td>
<td>.035</td>
<td>.74</td>
<td>8.75</td>
</tr>
<tr>
<td>.85</td>
<td>.035</td>
<td>.78</td>
<td>11</td>
</tr>
<tr>
<td>.9</td>
<td>.035</td>
<td>.84</td>
<td>13</td>
</tr>
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</table>
Ultra-short period undulators
RF & Laser based undulators offer advantages but demand excellent uniformity and are undeveloped.

**Good:**
- large aperture
- high fields
- smooth bore (wakefields)
- tunable

**Bad:**
- betatron motion
- power loss along waveguide modes and cutoffs

**Ugly:**
\[
\frac{\delta a_U}{a_U} \ll \rho
\]

RF waveguide undulators can work.

Beating can create larger periods

**Issues:**
- \(\cos(\pi f_s t) \sin(2\pi f_r t)\)
- \(800\text{nm} + 1\mu\text{m} = 20\mu\text{m}\)

Readily available laser technology
Efficient path to longer periods
Better than OPO/OPA?
Ripples ok?
A grating based undulator can produce an intermediate-period device

**Barriers:**
- Smith Purcell parasitic radiation
- Attosecond pulses and synchronization
- Low fields?
- Period limit? (300µm)

Beam powered devices have also been considered: Image charge undulator (Wakefield)

**Issues:**
Another beam?
Advantage over RF?
Energy loss?
Acronym challenged (ICU)

Y. Zhang et al., NIM A 507 (2003) 459–463
Laser guiding and laser technology
Guiding of the laser reduces the effects of diffraction and the Gouy phase shift

In practice, the fiber (waveguide) will be overmoded

\[ R_g \gg \lambda \approx 1 \mu m \]

On the other hand, a very small bore is required to obtain significant enhancement from guiding. We take

\[ 2R_g = 20 \ \mu m \]

The naive flux enhancement factor is simply

\[ \left( \frac{2w_0}{2R_g} \right)^2 = 4 \]

The brightness is enhanced further as the bandwidth may be reduced.

Electron beam transmission will be very challenging at low energies. There are many additional considerations such as vacuum, breakdown, plasma formation, etc.
Planar Bragg guiding...

Claim:
energy out is 2 OOM over free space, but only $10^{-6}$ photons per electron


Bragg waveguide setup. The electrons interact with a counterpropagating laser and emit x-ray radiation. The laser mode of interest has a TEM form inside the vacuum core. The mode is confined to a submicron cross section, enabling strong interaction not at the expense of interaction length.
Guiding of the (soft) x-rays is also possible

The phase space reduction factor is

\[
\frac{2\theta_c^2 L}{4\theta_c R_g} = \frac{\theta_c L}{2R_g} = \frac{1}{N_{zz}}
\]

Guiding in optical accelerator driven ICS is interesting:
- short pulse = higher damage threshold
- high rep rate = less laser energy per pulse
- fields in guide ~ fields in accelerator
Conclusions
A soft x-ray light source powered entirely by lasers and on a laptop scale seems possible

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Pellegrini and Travish
We have the opportunity to develop a suite of on-chip particle beam tools

- **guns**
- **monolithic structures**

- **sub-relativistic structures**
- **muons, protons, ions**

- **undulators**
- **coherent THz/x-ray sources**
- **IFEL accelerator**

- **deflecting cavities**

- **focusing**

- **ultra-fast sources**

- **ICS Gamma-Ray Source**

**all using laser-driven dielectric structure**
Technical development level will decide which optical scale structure is of interest

Very low charge is good for very short time scales

Killer app for optical structure based light source still needs to be identified
prediction
A laser “add-on box” to up-convert to x-rays and based on an optical-scale accelerator will be available in 10 years.