GALAXIE: A Compact X-ray FEL

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Overview

S-Band Photoinjector

Skew Quads

Dielectric Accelerator

Microquads

THz Undulator

40-50 keV Coherent X-rays

Mid-IR Pulsed Laser
Overview

- Wavelength = 5 \( \mu \text{m} \)
- Pulse duration = 1 ps
- Pulse energy = 500 \( \mu \text{J} \)
- Repetition rate = 10 Hz (later, up to 10 kHz)
Overview

- Pulse duration = 1 ps
- Pulse current = 1 A
- Beam energy = 3-8 MeV
- Normalized emittance $= \epsilon_x^* = \epsilon_y^* = 2 \times 10^{-8} \text{ m} \cdot \text{rad}$
- Spot size < 100 $\mu$m
Overview

- Skew-quad triplets for flat ↔ round transformations
- Narrow emittance $= \epsilon_y^* = 2 \times 10^{-9} \text{ m} \cdot \text{rad}$
- Wide emittance $= \epsilon_x^* = 2 \times 10^{-7} \text{ m} \cdot \text{rad}$
Final beam energy = 1 GeV
Peak acceleration gradient > 1 GeV/m
Beam opening dimensions = 2 \( \mu m \times 500 \) mm
Final longitudinal bunching factor > 300
Final longitudinal momentum spread = \( \sigma_{\delta p/p_0} < 10^{-4} \)
- Need recoupling to accommodate multiple accelerator segments
- Field gradients > 3 kT/m
- Overall transverse extent less than a few mm
- Overall longitudinal extent approximately 100 µm
Overview

- Undulator wavelength $\lambda_u \approx 100 \mu m$
- Undulator strength parameter $K = eB\lambda_u/2\pi mc \approx 0.1$
- Required deflecting force $\approx ec(10 \text{ T}) = 3 \text{ GeV/m}$
- 1D Pierce parameter $\rho = 10^{-4}$
- Gain length $L_g = \lambda_u/4\pi\sqrt{3}\rho \approx 50 \text{ mm}$
The dielectric accelerator requires fields in excess of GV/m.

High power / high rep rate laser systems are commercially available at 800 nm. What is the rationale for pushing into the mid-infrared?

- Easier device fabrication (e.g., 800 nm holes instead of 130 nm holes).
- Can work with larger emittance (e.g., $10^{-9}$ m · rad instead of $3 \times 10^{-11}$ m · rad).
- Nonresonant transverse focusing is stronger.
- Mitigate space charge and wakefield problems.
- Suppress multiphoton ionization for possible higher device breakdown fields.
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Technical Approach

Generation of 2 \( \mu \text{m} \) pump:

- Two-stage OPA
- \( \lambda_{\text{pump}} = 792 \text{ nm} \), \( \lambda_{\text{signal}} = 1.29 \mu \text{m} \), \( \lambda_{\text{idler}} = 2.05 \mu \text{m} \)
- Type II phase-matching in BBO (negative uniaxial)
- Use supercontinuum seed in first stage for passive CEP stabilization
- Relatively small group velocity mismatch among the three wavelengths
Results at 2 micron

Full-power 2 micron pump demonstrated with good beam characteristics:

\[ M^2 = 1.14 \pm 0.10 \]
Results at 5 micron

Have demonstrated 5 micron generation in ZGP:

![Graph showing intensity versus wavelength]
Luigi Faillace, “Recent Advancements in RF Guns”
Wednesday Parallel Session B at 15:30

- Number of cells = 1.6
- Peak field = 160 MV/m
- Coaxial coupling
- High launch phase of 75 degrees
- Magnetize beam for subsequent emittance splitting
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The dielectric accelerator has approximate 2D Cartesian symmetry, with a narrow (2 µm) beam opening in the 2D plane and a wide (500 mm) beam opening in the extruded dimension. This permits large charge fluxes by:

- Reducing space-charge self-forces
- Reducing coupling to destabilizing transverse wakefields

Therefore, we need round ↔ flat skew-quad triplets before and after the accelerator.
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Therefore, we need round \( \leftrightarrow \) flat skew-quad triplets before and after the accelerator.
Dielectric Accelerator

Accelerator eigenmode\(^1\)

- Resonant spatial harmonic provides acceleration.
- Nonresonant spatial harmonics provide focusing.
- Hole diameters approximately 800 nm.

Microquads

Anticipate the need to break the dielectric accelerator into multiple segments. Why?

- Wafer size is limited 100 mm.
- To introduce beam diagnostics.
- To replenish laser-power reservoir.
- To adjust sensitive parameters, particularly $\phi_0$.

Need to recouple beam back into each segment. To keep the accelerator short, use microfabricated quadrupoles.

Rob Candler, “Microscale magnetic flux sources for electron beam manipulation” Wednesday Parallel Session A at 10:20

Jere Harrison, “Surface-micromachined Electromagnets for 100 $\mu$m-scale undulators and focusing optics,” Thursday Poster Session
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Microquad Fabrication

- Silicon substrate
- Bosch etch 10 $\mu$m deep pattern
Microquad Fabrication

- Insulation layer between silicon substrate and lower windings
- Silicon nitride via PECVD or SiO$_2$ via thermal oxidation
Microquad Fabrication

- Copper for lower windings and electrodes
- Sputter Ti/Cu seed, electroplate, and CMP
Microquad Fabrication

- Silicon nitride insulates yoke from lower windings
- Magnetic yoke (e.g., NiFe 80/20 — $B_{\text{sat}} = 1$ T, $\mu_{\text{rel}} = 8000$)
Microquad Fabrication

- Mold for vias and more PECVD insulation
Gold for upper windings and winding vias
Microquad Fabrication

- Strip mold and seed
Microquad Results

Field Gradient in aperture is 3.3 T/mm = 3,300 T/m!!

To obtain saturated output at 40-50 keV in a 1-2 meter undulator, we want $\lambda_u \approx 100 \, \mu m$ and $K = 0.1$. One such design is an electromagnetic standing wave helical undulator operating in the THz regime:
THz Undulator

Very large axial fields of 10 T and 3 GV/m. Careful electromagnetic design reduces power density at the walls:

Two coupling ports for independent excitation of two polarizations.
Genesis FEL simulation shows saturation at 2 meters:
A model scaled to X-band has been fabricated and tested:

- Undulator wavelength $\lambda_u = 1.39 \text{ cm}$
- 50 MW @ 11.424 GHz give $K=0.7$ (equivalent to axial fields of 0.5 T and 160 MV/m)
- Beamline test at NLCTA shows visible FEL radiation
Fields in a photonic accelerator

Dielectric periodic along the beam axis,

\[ \epsilon(x_\perp, z) = \epsilon(x_\perp, z + d) \]

Longitudinal electric field of eigenmode having angular frequency \( \omega \) and wave vector \( k \),

\[ E_z = -iE_0 \sum_{n_z} a_{n_z} e^{i(k_{n_z}z - \omega t)}, \]

where \( a_{n_z} \) are the spatial harmonic coefficients and

\[ k_{n_z} = k + 2\pi n_z / d \quad (-\pi/d < k \leq \pi/d) \]

Assume dielectric has mirror-symmetry about \( xz \) and \( yz \) planes so that there are four possible modal symmetries. Look for speed-of-light bandgap modes having electric fields even under both types of reflection.
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Eigenmode is a superposition of spatial harmonics, each having the same frequency $\omega$, but a different phase velocity $v_{nz} = \omega / k_{nz}$.

Particle injection velocity $v_{n_0}$ synchronized to the resonant spatial harmonic $n_0$. Resonant wave can provide stable longitudinal acceleration, but, consistent with Earnshaw’s theorem, is also transversely defocusing.

Nonresonant spatial harmonics $n_z = n_0 + q$, where $q \neq 0$, provide rapidly oscillating force that transversely stabilizes particle via time-averaged ponderomotive force.
Spatial harmonics

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Transverse secular equation of motion

\[
\frac{d^2 Y}{dz^2} = Y \left\{ \frac{\alpha_0 k_0^2}{\gamma_0^3 \beta_0^2} \cos \phi - \frac{\alpha_0^2 \omega^2}{2 \gamma_0^2 \beta_0^4 \omega_0^2} [(B + D) + (C + E) \cos 2\phi] \right\}
\]

For example, the “transverse-direct” coefficient is

\[
B = \sum_{q \neq 0} \frac{E_q^2 k_q^2}{E_0^2 q^2} (1 - \beta_0 \beta_q)^2
\]

Origin of terms:

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Slow modulation for stronger transverse focusing

- Slowly modulating photonic waveguide over $N$ unit cells decreases $\omega_0 \sim \beta_0 \omega / N$ and correspondingly increases ponderomotive focusing.
- Creates a slow sideband and a fast sideband.
- Focusing force vanishes for $k_q = \beta_0^2 k_0$. Synchronizing to the fast sideband avoids this possibility.
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At low energy, the strong nonresonant longitudinal wave produces extra transverse stabilization.

In figure shown ($\gamma = 6$), 40% of transverse stabilization is due to longitudinal motion.
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Accelerator mode

- Eigenmode of the dielectric structure intrinsically provides both acceleration and transverse stabilization.
- Maximum longitudinal field / maximum dielectric field = 1.41.
- See movie.
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Spatial harmonic spectrum
Drive waves are 180 degrees out-of-phase to excite the even-$\gamma$ symmetric accelerator mode.

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Coupler eigenmode

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- See movie.
Anti-crossing at coupling between fast group velocity drive mode and slow group velocity accelerator mode.
Coupler temporal evolution

See movies.
Buncher (black portion of line, length = 500 mm):
- Adiabatically ramp resonant field to induce bunching
- Nonresonant field is present for focusing

Accelerator (blue portion of line, length = 1500 mm):
- Accelerate from $\gamma_0 = 6$ to $\gamma_0 = 2000$
- Adiabatically ramp synchronous phase $\phi_0$ to its final value
- Unique dynamics of an optical electron accelerator (high $\gamma_0$ and low $\alpha_0$) yield “adiabatic bunch compression” proportional to $\gamma_0^{-3/4}$.

See movie.
Assuming an initially flat beam current of 1 A, the peak bunched current is

\[ 1 \text{ A} / \sqrt{2\pi \sigma^2} = 1050 \text{ A} \]

Still need to reduce longitudinal momentum spread by an order-of-magnitude. There is still room for improvement in the initial bunching.
Previously, Soong\textsuperscript{2} made measurements at up to 2.2 $\mu$m:

- Pulse duration $\tau = 1$ ps
- Silicon damage threshold $F_{th} = 0.35$ J/cm\textsuperscript{2}
- Breakdown field $E_{\text{peak}} = \sqrt{F_{th}/\tau \epsilon_0} = 1.15$ GV/m.

No data available for short pulse mid-infrared breakdown in silicon or sapphire. So, testing done with frequency doubled CO₂ laser at BNL:

- Maximum pulse energy = 6 mJ at 5 micron
- Pulse duration $\tau = 5$ ps
- Maximum peak intensity = 15 J/cm²
- Sapphire damage threshold $F_{th} = 14$ J/cm²
- Silicon damage threshold $F_{th} = 0.61$ J/cm²

Scaling these 5 micron results to 1 ps pulses, we obtain:

- Silicon breakdown field = 1.5 GV/m
- Sapphire breakdown field = 7.3 GV/m
Simple cantilevered structure

- Simple non-functional single-mask design for developing fabrication recipes.
- SOI wafer.
- Plasma etch for pattern in upper silicon layer.
- Wet etch for undercutting the buried oxide.
Photolithography

GDS mask at 5X resolution:

Patterned photoresist [Max Ho, UCLA Nanolab]:

Fabricated structure

[Max Ho, UCLA Nanolab]
Optical test chip

- Functional two-mask design for optical testing.
- Gray layers are silicon. Blue layer is SiO$_2$.
- Shown here, the layers are 1 $\mu$m thick. Looking ahead to the stacked structure, we will investigate thick photonics ($\sim$ 10 $\mu$m thick).
- Use gentle bends for the drive waveguides.
- Two laser inputs on the right. For mode spectroscopy, use mid-infrared CW quantum cascade laser.
- Two outputs on the right go to spectrometer/detector.
- Adjusting relative phase of inputs changes symmetry of excited modes.
The future – stacking GALAXIE

[A. Tandaechanurat et al., Demonstration of high-Q three-dimensional photonic crystal nanocavity embedding quantum dots, Appl. Phys. Lett. 94, 171115 (2009)]
The future – stacking GALAXIE

- To accommodate ribbon beam, structure must be around 500 $\mu$m tall
- Anisotropic ratio 500:0.8 is well beyond state-of-the-art
- Instead, stack multiple devices
Conclusion

Conceptual steps the GALAXIE accelerator structure has taken:

- Provide nonresonant transverse focusing.
- Couple power from a co-moving quasi free-space laser pulse.
- Compress bunches in excess of a factor of 1000 via adiabatic bunch compression.
- Mitigate space-charge and wakefield problems.

Fabrication continues to be a major challenge:

- Structure requires beyond state-of-the-art anisotropic etching.
- Can demonstrate concept in silicon, but a practical device would need to be built from sapphire.
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