Laser Systems for Particle Accelerators

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Laser technology for accelerators overview

Near-IR laser technologies

Mid-IR laser technologies

Mid-IR-ready 5 μm source for GALAXIE
Applications of lasers in accelerator science and technology

LWFA

DLA

EEHG / HGHG

Diagnostics

Ion acceleration

Photoinjectors
Evolution of laser technology: peak power and intensity

Electron Quiver Energy (eV) for λ = 1 μm

Laser Intensity (W/cm²)

1970

1980

1990

2000

Current Technology

Future

Perturbative Atomic Physics
Nonlinear Optics

Nonperturbative Atomic Physics
High Order Nonlinear Optics

Tunnel Ionization
High Temperature Plasma Formation
Bright X-ray Generation

Relativistic Plasmas
Hard X-ray Generation

Fusion Ignition
e⁺e⁻ Production
Nuclear reactions
GeV electron accel

Relativistic ions
Pion production
QED
Chirped-pulse amplification (CPA)

Strickland & Mourou (1985)
Optical parametric chirped-pulse amplification (OPCPA)

Two flavors of OPCPA

Nanosecond pump
- pump: usually Nd:glass/YAG/YLF
- seed: Yb:xxx, Nd:xxx or Ti:sapphire
- electronic synchronization usually sufficient
- spatiotemporal shaping of pump
- high peak power, low rep rate

Picosecond pump
- pump: usually Yb:YAG/glass/fiber
- seed: Yb:xxx, Nd:xxx or Ti:sapphire
- synchronization via supercontinuum generation
- lower peak power, high rep rate
- higher efficiency: innovative compression

UT Austin

MPQ, Germany
Evolution of laser technology: average power

- Yb$^{3+}$ fiber lasers demonstrated
- Snitzer, Cladding pumped fiber lasers
- "Rediscovery" of fiber lasers by Southampton
- Large mode area fibers
- Pump laser improvements

"Theoretical" Thermal Extraction Limit for Single Fiber

J. Dawson, LLNL
Fiber lasers are the enabling technology for high average power

Multimode pump is converted into single mode, diffraction limited beam.

J. Price, University of Southampton
Laser materials for short-pulse, bulk near-IR lasers

Desire: appropriate wavelength, small quantum defect, long upper-state lifetime (energy storage), gain bandwidth, low reabsorption at the laser wavelength

Pump diodes: 940 nm for Yb:YAG; 981 nm for Yb:KGW and Yb:KYW

Yb:Lu$_2$O$_3$ - 80% efficiency
Ti:sapphire laser - a scientific workhorse

+ commercially mature
+ ultrashort pulses
+ kHz rep rates possible
+ scalable to PW
+ high beam quality

- indirect pumping
- limited efficiency
- complexity
- difficult to scale to high average power

BELLA: Berkeley Lab Laser Accelerator

Pump: Nd:YAG/YLF/glass
Yb:YAG thin disk laser: “active mirror”


- usually Yb:YAG
- crystal thickness $\ll$ beam diameter; “active mirror”
- $\Delta T$ perpendicular to surface $\rightarrow$ low thermal lensing and depolarization
- simple scaling of average power with mode area
- limited by transverse ASE
- may require multipass pumping; high doping concentration
- excellent high energy amplifier (usually a regen)
CPA in thin disk Yb:YAG laser

100 Hz, 14% efficiency, <2 ps pulse duration, 113 mJ

100 Hz, 140 mJ, 4.8 ps pulse duration multi-J operation possible with cryogenic cooling
Yb:YAG innoSLab laser


- 20 mJ, 12.5 kHz, 830 fs
- up to 100 kHz
Fiber lasers are revolutionizing the high average power laser technology

- favorable surface/volume ratio, enabling unprecedented average powers
- two primary technologies: Yb:fiber (1 µm) and Tm:fiber (2 µm)
- high wall plug efficiency
- waveguiding effect suppresses detrimental effects present in bulk lasers, such as thermal lensing
- compatible with CPA
- robust and alignment-free (if bulk components can be avoided)

Challenges:
- long gain media (doping + waveguiding) and small mode area → high nonlinearity
- dispersion compensation
The present paradigm for further scaling of laser power is coherent combining

Nature Photonics 7, 258 (2013) - this morning!

**commentary**

The future is fibre accelerators

Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.
Coherent combining within a CPA system has been demonstrated


The femtosecond oscillator is an All Normal Dispersion (ANDi) femtosecond fiber oscillator, the generated pulses are positively chirped with a pulse duration of ~15 psec. After the femtosecond oscillator, the beams are first pulse stretched by a chirped pulse stretcher and then amplified in a 4x stage of GRIN rod amplifiers (GROD) with a pulse energy of ~10 nJ. The amplified pulses are then launched into a monolithic combiner where the pulses are combined coherently into a single beam.

The combiner used was a Binary Tree arrangement of beamsplitters and phase modulators. This arrangement is shown in Fig. 11. Combined power is found by direct calculation:

\[
P_{comb\_in\_phase} = P_{1\_out} + P_{2\_out} + 2\sqrt{P_{1\_out} \cdot P_{2\_out}} = \left(\sqrt{P_{1\_out}} + \sqrt{P_{2\_out}}\right)^2
\]

“Binary tree” arrangement of beamsplitters and phase modulators is used.
Tiled aperture combining of 64 fiber lasers


The polarization axis of the input and the output PM fibers are aligned parallel to each other. A pattern of interdigitated electrodes is etched in a PLZT electro-optic ceramic using ultrasonic methods. Each of the 4 outputs is further split into 16, leading to 64 amplified fibered laser outputs. The experimental setup is shown in Fig. 1. A continuous 1.55 µm laser is pre-amplified to 1W by a first Erbium-doped Polarization Maintaining Erbium-Doped Fiber Amplifier (PM EDFA). QWLSI: Quadriwave Lateral Shearing Interferometer.

Further developments will involve a high-speed camera operating in the >kHz range. The multi-dithering technique and feedback loop are used to achieve phase control. The device is based on a 2D diffraction grating, rotated by 45° with respect to the fiber array orientation. This grating generates 4 laterally sheared replicas in two dimensions of the laser output. The microlens array was realized by Suss MicroOptics on a silicon wafer with a pitch of 1500µm (±1µm). Focal length of each lenslet was chosen to be 5.77mm at 1.5µm to optimize the lenslet diameter and the beam diameter was 0.6 in our case. Microlens array quality was checked with respect to the pitch and focal regularity. The whole set of performed associated lenses. It consists of a thick polymethylmethacrylate (PMMA) plate periodically checked with respect to the pitch and focal regularity. The whole set of performed associated lenses. It consists of a thick polymethylmethacrylate (PMMA) plate periodically checked with respect to the pitch and focal regularity. The whole set of performed associated lenses. It consists of a thick polymethylmethacrylate (PMMA) plate periodically checked with respect to the pitch and focal regularity.
Divided-pulse amplification is appropriate for ps pulses

- efficient; convenient for narrow bandwidth pulses; easy alignment

Number of pulse replicas: $2^N$ ($N$ is the number of crystals)

CPA: <1 ps; DPA: >1 ps


2.2 ps, 1 MW demonstrated
Spectral beam combining


Temporal coherence is unnecessary
Limited to broader bandwidth

1 kW CW
2D diffractive coherent combining


\[ \eta_{MN} = \frac{\iint |\sum_{n,m} D_{m,n} \sqrt{I_{m,n}(x,y)} e^{i\phi_{m,n}(x,y)} + i\Delta\varphi_{m,n}}|^2 dxdy}{\iint \sum_{n,m} I_{m,n}(x,y) dxdy} \]

combining efficiency

15 amplifiers, 600 W
Nonlinear beam combining


- compatible with OPA/OPCPA
- active phase control unnecessary
Average power limitations of nonlinear optical materials

Fiber mid-IR sources based on Tm$^{3+}$

- higher mode areas are supported
- lack of fiber components at 2 μm
- pulsed operation with large pitched fiber (81 μm core): 2.4 mJ, 13.9 kHz, 15 ns, 33 W, $M^2 < 1.3$
- ultrafast oscillator: 31 nJ, 108 fs

Bulk solid-state lasers for mid-IR generation: Cr$^{2+}$ doped chalcogenides

Cr: ZnSe @ 2.45 μm

E. Slobodchikov et al., CLEO (2011)
- 1 GW, 300 μJ, 300 fs in a CPA system
- pump: Tm-fiber + Ho:YLF (2.05 μm)
- scalable to higher energies

Cr: ZnS @ 2.35 μm

- lower dn/dT than Cr:ZnSe
- supports 15 fs pulses
- mode-locked to 69 fs, 550 mW

Longer wavelengths: parametric mixing processes (DFG)
The GALAXIE design requires a 5 μm, <1 ps pump pulse

Dielectric laser acceleration could enable convenient production of tunable monochromatic X-rays for applications such as phase contrast imaging.

A photonic bandgap structure could guide an ultrashort laser pulse for electron acceleration.

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


Desire mid-IR wavelength (5 μm) pump pulse: damage and fabrication considerations.

Pulse energy: ~100’s of μJ; Pulse duration: <1 ps; High beam quality
Repetition rate: 10 Hz demonstration; >kHz for future systems
OPA vs OPCPA for mid-IR short pulse generation

As always with parametric systems, the most critical issue is the availability and performance of the pump laser.

OPA

- CPA pump
- Spectral broadening / filtering
- Optional phase compensation
- $\eta \sim 40\%$

OPCPC

- Ultrashort seed
- Spectral broadening / filtering
- Long-pulse pump
- OPA
- $\eta \sim 40\%

- scalable to high energies
- relatively complex
- compression is frequently lossy
- idler compression can be challenging

2–2.5 μm high-energy pump sources

Direct mid-IR laser pumping is desirable to reduce complexity and increase overall efficiency.

Good candidate pump: Cr:ZnSe (E. Slobodchikov and P. Moulton, CLEO 2011):
- Tm:fiber pumped scalable approach to produce high-peak power mid-IR pulses

\[ \frac{\Delta \lambda}{\lambda_0} = 0.49 \]

130 fs @ 2530 nm

350 μJ, 346 fs @ 2475 nm

Tm:fiber pumped Cr:ZnSe CPA system is a good candidate for direct OPA pumping at ~2.5 μm to produce 5 μm light.
Summary of technical approach for GALAXIE 5-μm source

- **Ti:sapphire commercial pump laser**: 15 mJ, 0.8 μm, 10 Hz
- **OPG/OPA 2 μm pump source**: 2 mJ, 2 μm, 10 Hz
- **OPG/OPA 5 μm source**: ~500 μJ, 5 μm, 10 Hz

Future: direct pumping by Tm/Ho/Cr-based high-energy short-pulse laser

**Materials**:
- BBO: 2 μm
- ZGP: 5 μm

**Graph**:
- Autocorrelation trace with a FWHM pulse duration of 346 fs.
  - Spectrum centered at 2475 nm with a FWHM of 37 nm.
BBO and ZGP crystals for mid-IR generation

- high nonlinearity
- broad bandwidth
- good transparency
- availability in large apertures
- relatively cost effective

idler center wavelength for 2 μm source
High-energy 2-μm pump source optical design

BS1, BS2, L1, L2, L3, L4, S1, S2, M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, DM1, DM2, DM3, DM4, C1, C2, WP, Delay1, Delay2
The high-energy 2-µm source is relatively compact

High-energy 2-µm OPA (2’x3’)

Single-shot autocorrelator

Spectral analyzer
Type I vs type II phase matching in BBO

For a type II cut crystal, parasitic SHG is suppressed by
• phase mismatch (~5° difference in optimal PM angle θ)
• $d_{\text{eff}} \sim 0$ (30° difference in optimal crystal cut angle φ)

This issue is resolved by the use of type II phase matching.

Type I $792.0(\text{e}) \rightarrow 2050.0(\text{o}) + 1290.6(\text{o})$
At $\theta = 19.9$, $\varphi = 90$ deg.
$d_{\text{eff}} = 1.95$ pm/V

SHG $2050.0(\text{o}) + 2050(\text{o}) = 1025.0(\text{e})$
At $\theta = 21.3$, $\varphi = 90$ deg.
$d_{\text{eff}} = 1.85$ pm/V

Type II(a) $792.0(\text{e}) \rightarrow 2050.0(\text{e}) + 1290.6(\text{o})$
At $\theta = 25.9$, $\varphi = 60$ deg.
$d_{\text{eff}} = 1.58$ pm/V

SHG $1290.6(\text{o}) + 1290.6(\text{o}) = 645.3(\text{e})$
At $\theta = 20.6$, $\varphi = 90$ deg.
$d_{\text{eff}} = 1.99$ pm/V
2.2 mJ pulses have been generated at 2 μm

<table>
<thead>
<tr>
<th>OPA 1</th>
<th>OPA 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8 μm pump: 795 μJ</td>
<td>0.8 μm pump: 14.3 mJ</td>
</tr>
<tr>
<td>1.3 μm signal: 58 μJ</td>
<td>1.3 μm signal: 3.65 mJ</td>
</tr>
<tr>
<td>(after energy losses on beam expander and dichroics)</td>
<td>2 μm idler: 2.2 mJ</td>
</tr>
<tr>
<td>1:7 beam expander</td>
<td>(after energy losses on beam expander and dichroics)</td>
</tr>
</tbody>
</table>

**OPA 1** (preamplifier): 2.5-mm type II BBO  
**OPA 2** (power amplifier): 1.94-mm type II BBO
High beam quality at 2.05 $\mu$m has been demonstrated

$M^2 = 1.14 \pm 0.10$

Average value of divergence

0.55 mrad of half angle
Pulse duration is consistent with near-transform limited pulses

2.05 µm pulses are 1.17x transform limited (38 fs FWHM vs 32 fs FWHM)

2.05 µm

0.8 µm pump

148 nm FWHM

27 nm FWHM

38 fs FWHM

1. Introduction

System design and experiments

Two beta barium borate (BBO) crystals offer high gain in each OPA stage and are scalable to high powers. In addition, they frequently rely on complex and unique pump laser designs. A more flexible approach to optical parametric chirped pulse amplification (OPCPA) is being developed in this wavelength range. While many of the proposed schemes are technically challenging due to the lack of robust, mature Ti:sapphire laser systems. Technologies, they often use compact growth techniques for Type II (e.h. -→ o.p. mode) amplification in BBO crystals. The crystals used in the first stage and the second stage OPA, respectively, exhibit ~0.04 cm aperture, which allows high gain in each OPA stage. The crystals are centered at 800 nm, but the Ti:sapphire laser pulses are 1.17x transform limited (38 fs FWHM vs 32 fs FWHM). The OPA is pumped by transform limited 2.0 fs pump pulses at 2.05 µm, thus reducing the required pump intensity to 40 mJ Pulses.

Recent progress in theoretical and experimental setup of two optical parametric amplifier (OPA) generations of Few cycle mid infrared (IR) laser pulses have been motivated by the quest for high harmonic generation techniques. The experimental setup depicted in Fig. 1 inset: 2D autocorrelation trace; 2,3 µm wavelength range. 

Mid Infrared laser pulses have been produced at 2.05 µm, 190.7 nm, 190.4 nm, and 190.7 nm. The pulse duration is consistent with near-transform limited pulses. 

The crystals offer a relatively small group velocity mismatch occurring in OPA and nonlinear materials. 

Power scalability. In addition to the use of nonlinear crystals, a more flexible approach to the use of a stable delay line, two beamsplitter (BS1 and BS2) is used to realize high gain in each OPA stage.

The crystals offer high gain in each OPA stage and are scalable to high powers. Two beta barium borate (BBO) crystals are used in the first stage and the second stage OPA, respectively. The crystals are centered at 800 nm, but the Ti:sapphire laser pulses are 1.17x transform limited (38 fs FWHM vs 32 fs FWHM). The OPA is pumped by transform limited 2.0 fs pump pulses at 2.05 µm, thus reducing the required pump intensity to 40 mJ Pulses.

The pulse duration is consistent with near-transform limited pulses.
2-μm pulses exhibit high energy stability

Pump pulses at 792 nm

Idler pulses at 2.05 μm

Signal pulses at 1.29 μm
5-μm source design

2.05μm pump

M1 M2 M4 M8 DM1 C2 DM2 DM3 M9 M10

L1 L2 L3 L4 L5 L6

BS M5 M6 Delay

M7

5μm seed

3.47 μm

5 μm
We are progressing with 5-μm source construction
5-µm seed pulse generation

We choose optical parametric generation (parametric fluorescence) in ZGP for a non-CEP stabilized system.

Pump: 200 µJ, 2 µm, 100 fs
2 mm pump beam
Passive carrier-envelope phase stabilization of the 5-μm pulse


### TABLE I. Phase properties of various OPA designs.

<table>
<thead>
<tr>
<th>OPA configuration</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump frequency, ω₀</td>
<td>ω₀</td>
<td>2ω₀</td>
<td>2ω₀</td>
</tr>
<tr>
<td>Central frequency of white light</td>
<td>ω₀</td>
<td>ω₀</td>
<td>2ω₀</td>
</tr>
<tr>
<td>Phase offset of pump, ψ₀</td>
<td>ψ</td>
<td>2ψ + π/2</td>
<td>2ψ + π/2</td>
</tr>
<tr>
<td>Phase offset of signal, ψ₁</td>
<td>ψ + π/2</td>
<td>ψ + π/2</td>
<td>2ψ + π</td>
</tr>
<tr>
<td>Phase offset of idler, ψ₂</td>
<td>−π</td>
<td>ψ − π/2</td>
<td>−π</td>
</tr>
<tr>
<td>Self-stabilization of ψ₁?</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

This design does not require a CEP-stabilized pump laser to achieve 5-μm pulse CEP stabilization.
Summary

- There is a need for energetic mid-IR pulses for DLA.
- Single-step production of ultrafast 5-µm pulses by OPA is desirable, but it awaits more development of mature pump laser technology (for example, Cr:ZnSe).
- Generated surrogate high-energy 2-µm pulses for pumping 5-µm OPA using two-stage OPA.
- Generated broadband 5-µm seed pulses.

*In progress: construction of a 2-µm pumped 5-µm source*

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