Development of high average power fiber lasers for advanced accelerators

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Conceptual LPA Collider

- Based on 10 GeV modules
- Quasi-linear wake: e− and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules

LASER DRIVER:
- Requires high rep-rate (10’s kHz)
- Requires development of high average power lasers (100’s kW)
- Requires lasers with high wall-plug efficiency (>25%)

Leemans & Esarey, Physics Today, March 2009
ICFA-ICUIL Joint Task Force Strategy Workshops on “High Power Laser Technology for Future Accelerators”

- 1st Workshop at GSI Darmstadt, April 9-10, 2010
- 2nd Workshop at LBNL Berkeley, September 20-22, 2011

Objectives:
- comprehensive survey representing community consensus of requirements for colliders, light sources and medical applications
- identify future laser system requirements and key technological bottlenecks
- provide vision for technology paths forward to reach the survey goals

Dielectric Laser Accelerator Workshop at Palo Alto, September 2011
### Main requirements for high power fiber laser based advanced accelerator drivers (for select applications)

<table>
<thead>
<tr>
<th></th>
<th>LPA collider (10GeV stage)</th>
<th>LPA – Bella style (10GeV)</th>
<th>$\gamma - \gamma$ colliders</th>
<th>Dielectric Laser Accelerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall-plug Efficiency</td>
<td>&gt;25%</td>
<td>&gt;5%</td>
<td>&gt;25%</td>
<td>&gt;25%</td>
</tr>
<tr>
<td>Average Power</td>
<td>480kW</td>
<td>3 - 40kW</td>
<td>100kW</td>
<td>1-10kW</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>15kHz</td>
<td>1 kHz</td>
<td>Burst mode</td>
<td>100MHz – 1GHz</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>32J</td>
<td>3 - 40J</td>
<td>5J</td>
<td>100nJ – 10µJ</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>100fs - 200fs</td>
<td>~70fs</td>
<td>1ps</td>
<td>100fs – 1ps</td>
</tr>
<tr>
<td>Pre-pulse contrast</td>
<td>Better than $10^9$</td>
<td>Better than $10^9$</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Preferred $\lambda$</td>
<td>~1µm</td>
<td>~1µm</td>
<td>~1µm</td>
<td>~2-4µm</td>
</tr>
</tbody>
</table>
Follow-up activities:

DOE Workshop on “Laser Technology for Accelerators”
Jan 23-25, 2013 Napa, CA

- Summary Report in 2013 (Wim Leemans)
- Laser Accelerator Stewardship Program being established by DOE HEP

International Coherent Amplification Network (ICAN)

- Phased array of femtosecond fiber lasers for driving Wakefield-based particle colliders
- 18 month pilot paper study, EU/FP7 funded
Why fiber lasers?

• Principal advantages inherent in the technology:
  – Possibility of high efficiency
    • Currently: kW cw ~35% WPE, pulsed ~ 25% WPE
    • In the future: 40% - 50% WPE anticipated
  – Possibility of high power output
  – Possibility of diffraction-limited beam output
  – Possibility of compact “monolithic” integration

• Principal challenges inherent in the technology:
  – Pulse energy limitations
  – Average power limitations for a single fiber (particularly for ‘special’ signal formats: narrow linewidth, single-mode, ultrashort pulse, etc.)
    • for example ~ 10kW to 20kW for single-mode cw; 1kW – 2kW for narrow-linewidth cw
  – Bandwidth limitations due to gain narrowing
    • For example: in 100µJ to 1mJ FCPA output pulses are typically >300fs
Yb-doped fiber wall-plug efficiency

- Optical-to-optical efficiency up to ~85%
  - Low quantum defect (pumping at 940nm, 980nm or ~1010nm → signal at 1030nm - 1080nm)

- Pump diode electrical-to-optical efficiency 45%- 55% (commercial), to >65% (state-of-the-art)

- Additional “structural” losses of diode-to-fiber, fiber-to-fiber, etc., coupling with ~80% - 90% efficiency:
  - For example: 85%(fiber)x45%(diode)x80%(structural) = 30% WPE

- In ultrafast fiber lasers there are additional losses:
  - For pulsed amplifiers at 1kHz -10kHz some pump is wasted on ASE between pulses
  - “signal processing” losses: pulse compression (80% - 90%), beam combining (>90%), pulse stacking (>90%), etc.
Average powers are limited by:
- Thermal effects
- Nonlinearities:
  - FWM, SRS, SBS, TMI (transverse modal instability)
- Optical damage
Pulse Energy Limitations

- Optical damage

![Graph showing pulse energy limitations for different core sizes.](chart.png)
Pulse Energy Limitations

- Optical damage
- Self focusing

![Graph showing Pulse Energy Limitations for 135µm core PCF rod and 55µm core CCC with self-focusing indicated.](image-url)
Pulse Energy Limitations

- Optical damage
- Self focusing
- Stored energy

![Graph showing pulse energy limitations for different core sizes](image)

- 135µm core PCF rod
- 55µm core CCC

Energy, mJ vs Duration, ns
Fiber CPA is needed for high energy ultrashort pulse generation

Pulse Energy Limitations

- Optical damage
- Self focusing
- Stored energy
- Ultrashort pulse peak power limitations due to SPM and FWM

B-integral is ~1:

\[ B = \frac{2\pi}{\lambda} \int n_2 I(z) \, dz \]

Diffraction-grating compressor:  
~1ns $\Delta T_{\text{stretch}}$ per ~10cm grating size
Pulse Energy Limitations

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B-integral is \( \sim 1 \):

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Principal Challenge for Fiber Laser Based LPA Drivers

- High pulse energies & average powers: 32J/15kHz/480kW for 10GeV collider stage

Solution: Coherently combine multiple parallel FCPA channels

**Challenge**
100µJ – 1mJ per FCPA channel $\Rightarrow$ $\sim 10^4$ – $10^5$ parallel channels!
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Spatial Beam Multiplexing


« The future of Accelerator is Fiber »
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**Challenge**
100µJ – 1mJ per FCPA channel ➔ ~10^4 – 10^5 parallel channels!

• Technical challenges associated with very large arrays:
  – Coherent locking of >10^3 channels
  – Spatial combining of >10^3 broad-band beams at 100’s kW of average power
  – Cost, size and complexity of such large arrays
Theoretically predicted array size scalability with in-channel phase and amplitude noise

Combining efficiency “saturates” at large channel counts $N$, because combined power proportional to $N$ and noise – to $\sqrt{N}$.

State-of-art 4-channel FCPA-array coherent combining demonstrations

1st 4-channel FCPA ‘monolithic’ array demonstration at low power

4-channel FCPA array demonstration at high power using PCF rods


94.3% efficiency for over 1 hour

Reset tests

After each reset (blocking of the signal to the feedback detector) combining recovers instantaneously.

Types of Spatial Beam Coherent Combiners

• Binary-tree arrangement:
  – Parallel

  [Diagram showing parallel binary tree with T=50% transmission at each branch]

  Complex spatial arrangement

• Diffractive optical element

  [Diagram showing complex spatial arrangement with T=50%, T=33.3%, T=25% transmission]

  Spatial dispersion

– Serial (folded spatially)

  [Diagram showing serial arrangement with T=50%, R=100%]

For $N^{th}$ beam: $T_N = 1/N$

Fiber chirped-pulse-amplifier array is complex

Monolithic Fiber Amplifier

- Pump diode
- Yb-fiber
- WDM or Pump combiner
- Isolator
- 1:N splitter
- AOM
- FA
- EOM
- SM PZT
- Amplified stretched pulses

Stage I
(1 branch)

Stage II
(N branches)

Stage III
(N^2 branches)

Monolithic integration is essential
Fiber chirped-pulse-amplifier array is complex

Monolithic Fiber Amplifier

Stage I
(1 branch)

Stage II
(N branches)

Stage III
(N^2 branches)

LPF with up to 135 µm core
Fiber chirped-pulse-amplifier array is complex

Stage I
(1 branch)

Stage II
(N branches)

Stage III
(N^2 branches)

CCC with up to 55 um core
Summary of array-size related issues

• Coherent phasing with increasing number of channels:
  – In principle scales gracefully with the array size
  – However, technical implementation of phase error tracking and correction becomes increasingly difficult

• Spatial combining with increasing number of beams:
  – Becomes exceedingly difficult beyond $N \sim 10^2$

• FCPA array size, complexity and cost constitute a major practical challenge, which increases rapidly with the number of channels
Coherent phasing with increasing number of channels:
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- However, technical implementation of phase error tracking and correction becomes increasingly difficult

Spatial combining with increasing number of beams:
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FCPA array size, complexity and cost constitute a major practical challenge, which increases rapidly with the number of channels
Principal solution: Combine time-domain and spatial-domain multiplexing

Temporal Pulse Multiplexing

Spatial Beam Multiplexing

100 – 1000 pulses

10 – 100 parallel channels
Periodic pulse train (after stretcher)

N identical parallel coherently combined amplification channels with identical signals in each

From a pulse source

Trigger from a pulse source

Modulation-error recognition and modulation control, stacker cavity locking control

Phasing-error recognition and phase-locking electronics

Amplified and combined pulse-burst

To compressor
Coherent Pulse Stacking (CPS) in a GTI type of a resonant cavity

Input burst amplitudes and phases are selected such that:
- Pulses before the last one destructively interfere for front-mirror reflection – pulse burst is stored in the GTI cavity as a single pulse
- Last pulse constructively interferes at the front mirror to produce a single output pulse – stored energy is extracted
Proof-of-Principle Experiments with ns and fs pulses

Mode-lock Laser + Stretcher (for fs EXP) OR CW Laser (for ns EXP)

Monitor signal

AM & PM

SMFA

LMA Amp.

CCC Amp.

HWP

PBS

Monitor Det.

Feedback

PZT Mirror

GTI Stacker

Input

Stacked Output

Compressor

Output

ns EXP

fs EXP
**CPS Experimental Results**

**Nanosecond Experiment**
- Input
- Stacked Output
- 10kHz inter-burst repetition rate
- 200MHz in-burst repetition rate
- Up to 12W/1.2mJ per stacked pulse
- 93% efficiency (due to 93% folding mirror)
- Enhancement 2.5 times
- Contrast ~17dB

**Femtosecond Experiment**
- Input
- Stacked Output
- 97% efficiency
- 125MHz in-burst repetition rate
- Autocorrelation 600fs

**Input/Stacked pulses:**
- 1ns duration
- 10kHz inter-burst repetition rate
- 200MHz in-burst repetition rate
- Up to 12W/1.2mJ per stacked pulse
- 93% efficiency (due to 93% folding mirror)
- Enhancement 2.5 times
- Contrast ~17dB
Scalability of the Coherent Pulse Stacking (CPS) Technique

- Multiplexing several (8 to 15) GTI cavities enables large $(10^2 - 10^3)$ pulse stacking/peak-power enhancing factors.

- Design example of a 8-multiplexed GTI cavity pulse stacker:

Input 81-pulse burst

Output solitary stacked pulse

GTI traveling-wave cavities can be compactly folded as Herriott cavities

$N$ bounces in the cavity:
$cavity \, d = L/N$
CPS can enable extracting all stored energy with negligible nonlinearity

- Optical damage
- Self focusing
- Stored energy
- Ultrashort pulse peak power limitations due to SPM and FWM

B-integral is \( \sim 1 \):

\[
B = \frac{2\pi}{\lambda} \int n_2 l(z) \, dz
\]
Other time-domain multiplexing approaches

Divided Pulse Amplification (DPA)

- Splitting and combining stages
- Small number (N ~ 4 to 10) of stacked pulses
- Delay line length exponentially increases with the number of pulses $2^N$

Other Key Technical Issues for Fiber Laser Based LPA Drivers

• High pre-pulse contrast of $>10^9$ is required

![Graph showing normalized intensity vs time](image)


• Requires operation at low B-integral values
• Requires dispersion and phase compensation techniques
Other Key Technical Issues for Fiber Laser Based LPA Drivers

• Pulse duration <200fs is required

1.45mJ and 800fs result


• Coherent Spectral Beam combining can address it

Summary/Future Outlook

• Technical concepts exist to address all principal FCPA based LPA driver design challenges
  – Temporal and spatial multiplexing can lead to relatively small array sizes (~\(10^1\) to \(10^2\)), significantly reducing cost and technological complexity
  – Objective will be to extract all stored energy per amplifier without detrimental nonlinear effects, thus improving pulse fidelity (duration and pre-pulse contrast)
  – Spectral coherent combining can be used to achieve required pulse durations in the 50fs -200fs range

• This can enable next-generation TW – PW LPA drivers operating at kHz repetition rates

• There are numerous other important technical issues that are necessary to address:
  – Developing techniques for achieving high pre-pulse contrast
  – Optics for high power beam combiners and pulse compressors
  – pulsed laser efficiency optimization
  – .....