Coherent Beam Stacking Enabled Compact, Energy Scalable, and Several Optical Cycle Capable Ultrashort Pulse Post-Compression for the Next-Generation LWFA Drivers

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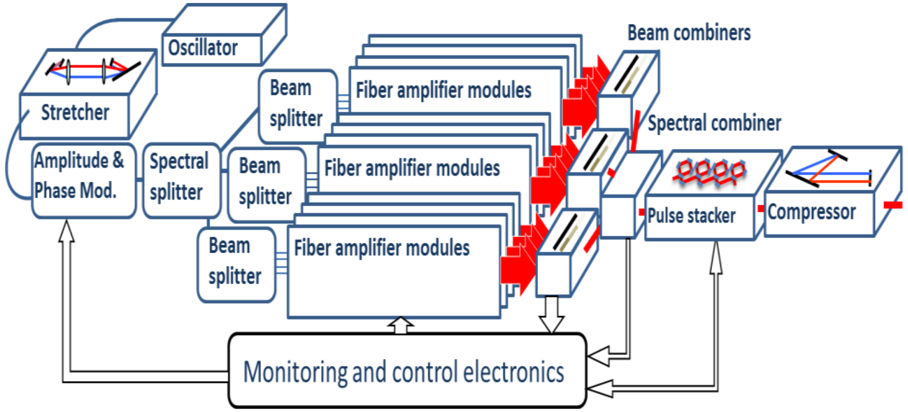
High Energy, High Rep Rate, Ultrafast Sources Needed

- Laser Wakefield Accelerators are in need to high efficiency, high energy, high repetition rate driving sources with <30fs pulse durations
- Current Fiber CPSA architecture is scalable to J level energies at 10kHz repetition rates, but pulse durations are limited by the gain bandwidth of Ytterbium and gain narrowing of the power amplifiers to somewhere in ~50-100fs range
- Spectral combining can be used to increase the bandwidth, but adds complexity to the system

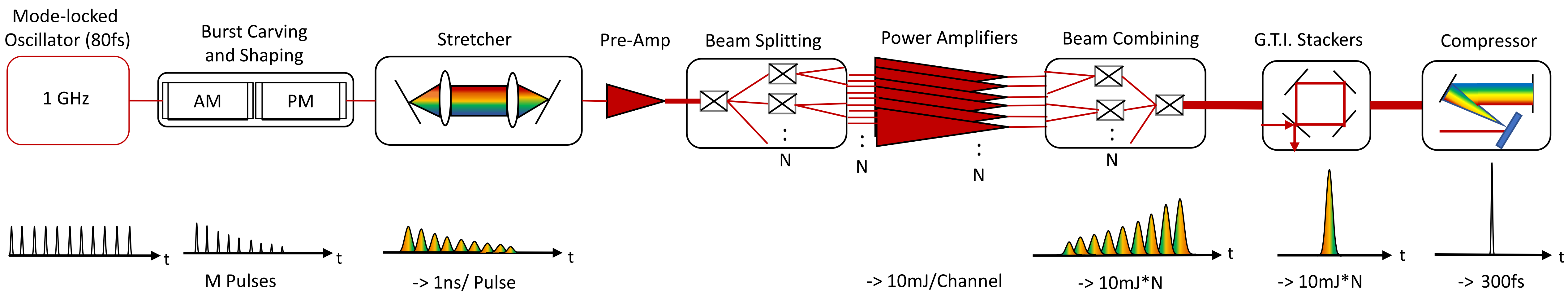


- Here we present a new CPSA-compatible post-compression method for achieving ~30fs pulses potentially scalable into TW-PW peak power range

Mourou, G., Brocklesby, B., Tajima, T., & Limpert, J. (2013). The future is fibre accelerators. *Nature Photonics*, *7*(4), 258–261.

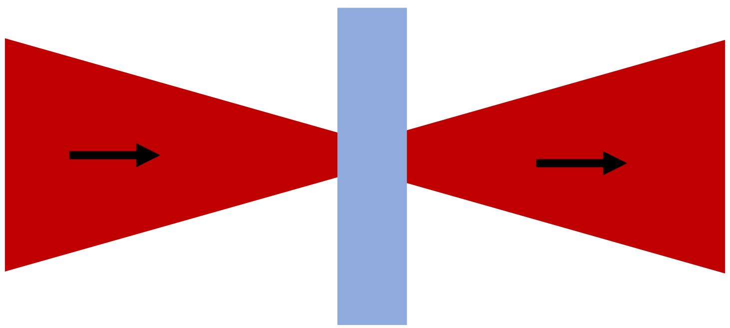
Coherent Pulse Stacking Amplification

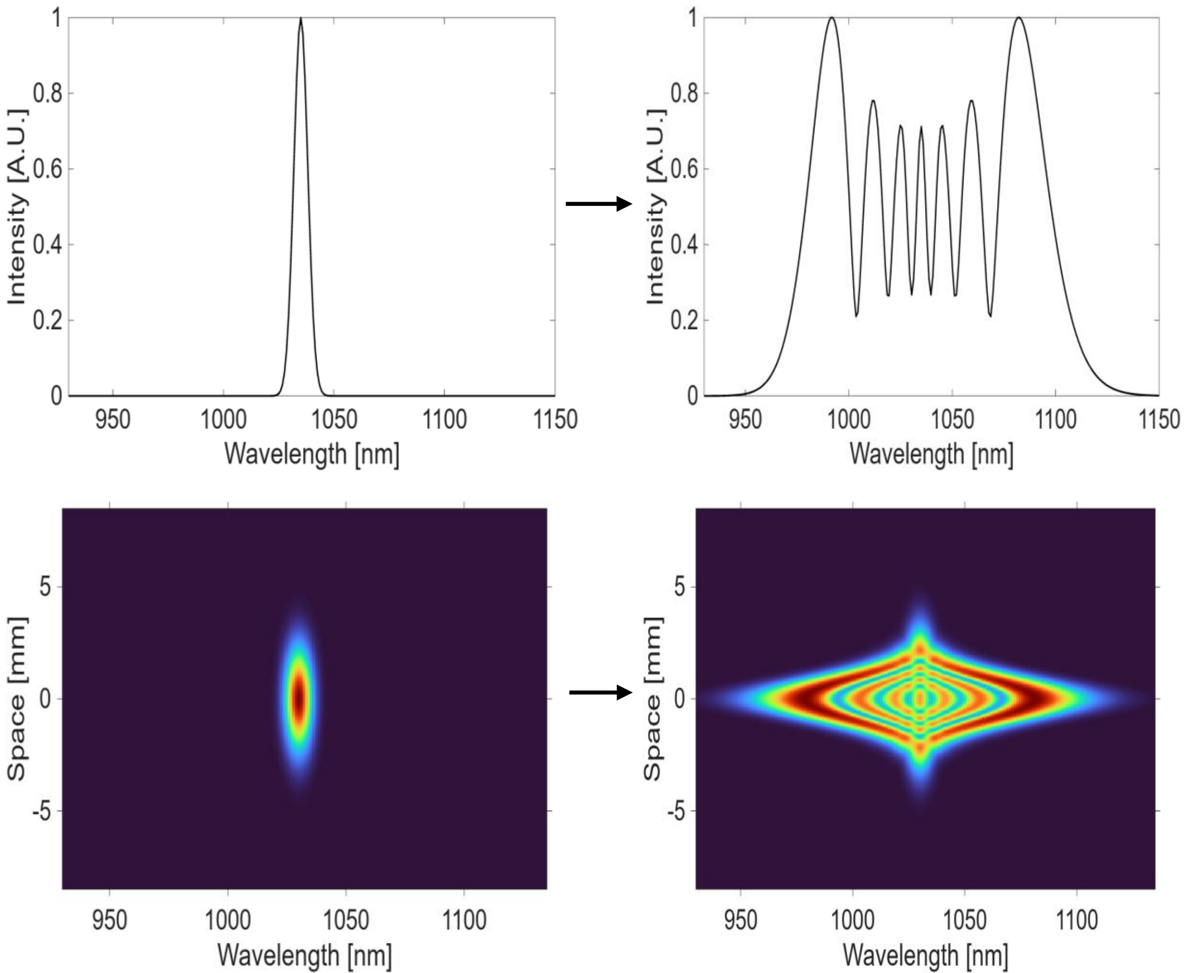
- Temporal energy scaling through coherent pulse stacking
  - Carefully crafted input pulse bursts enable extraction of all amplifier stored energy
  - Experimentally shown (~%90) stacking efficiency of bursts into a single pulse using G.T.I. stackers
- Spatial energy scaling through spatial combining
  - Comines N channels with M pulses per burst
  - Experimentally shown (%90+) combining efficiency



Nonlinear Post-compression: Theory

- Self Phase modulation used to broaden the spectrum of the pulse
- In free space it produces a spectrally inhomogeneous beam
- Fiber don't have this problem, but they can't support high energies
- For high energies multi-pass cells (MPC) are the solution

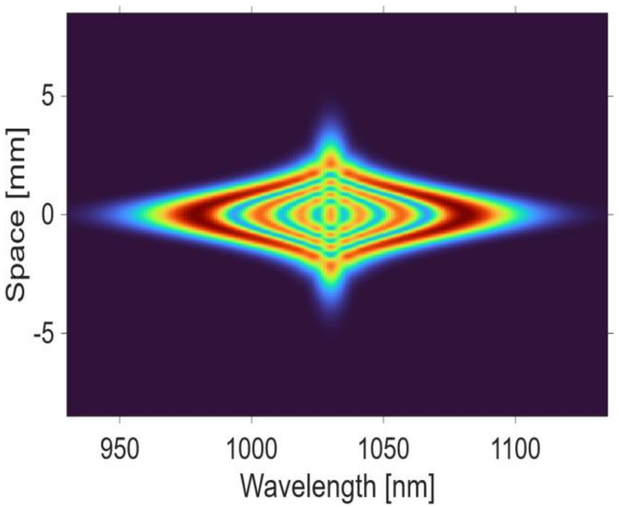




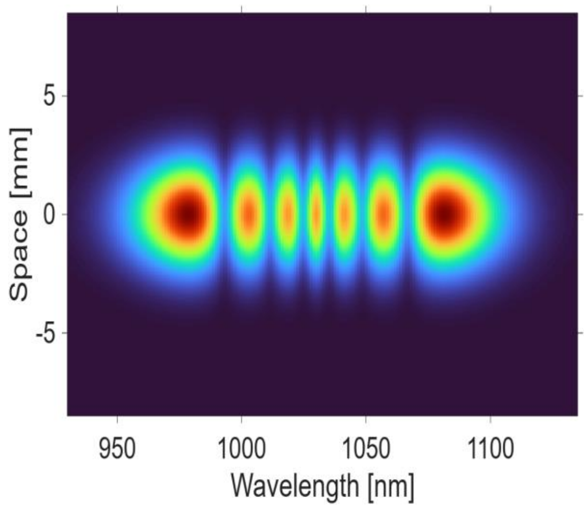
Nonlinear Post Compression: State of the Art

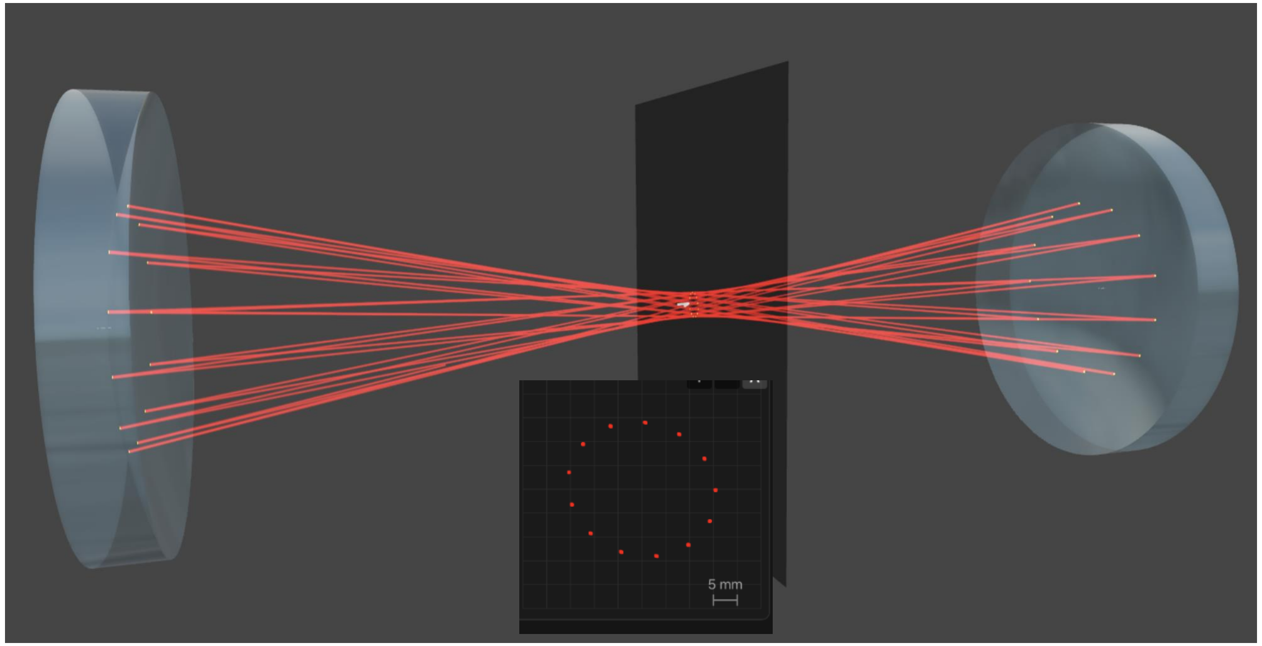
- Gas MPC's are robust, and less complex than their counterparts
- Similar to waveguides these cavities maintain excellent spatio-spectral homogenity
- Size scales with pulse energy
- Highest demonstrated energy is 200mJ in 10m long cell
- Kw average powers have been demonstrated

300fs, 4.5π free space spectral broadening



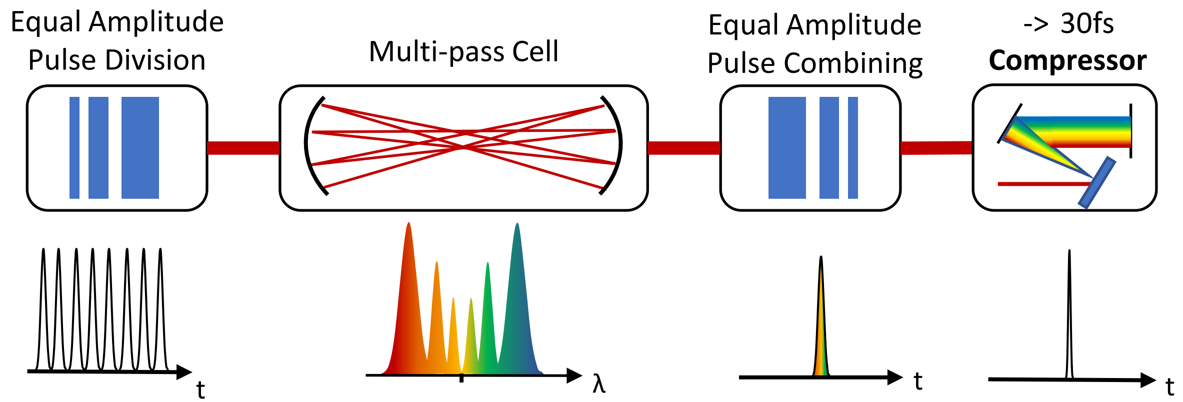
300fs, 4.5π MPC spectral broadening

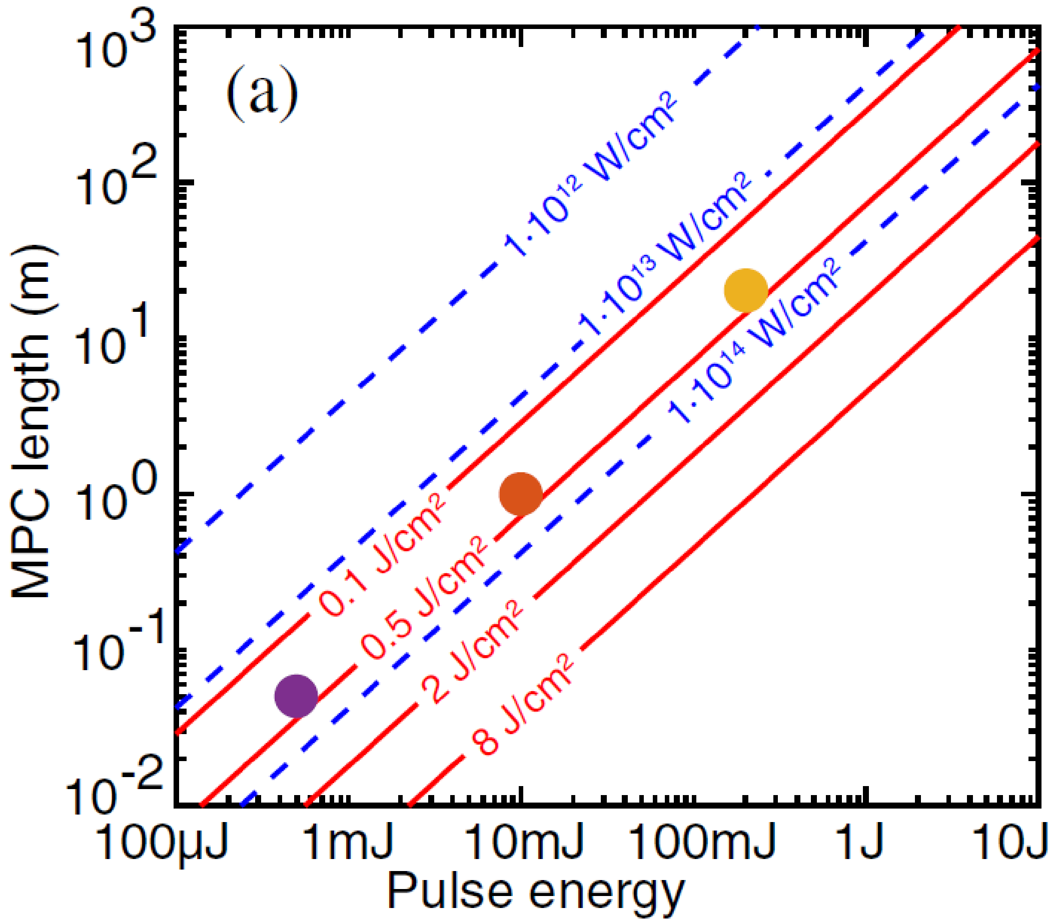




Nonlinear Post Compression: Limitations

- Material LIDT restrictions
- Gas ionization restrictions
- Nonlinear per transit restrictions
- Size scales with pulse energy
- 1 Joule estimated at 50m
- Divided Pulse Post Compression





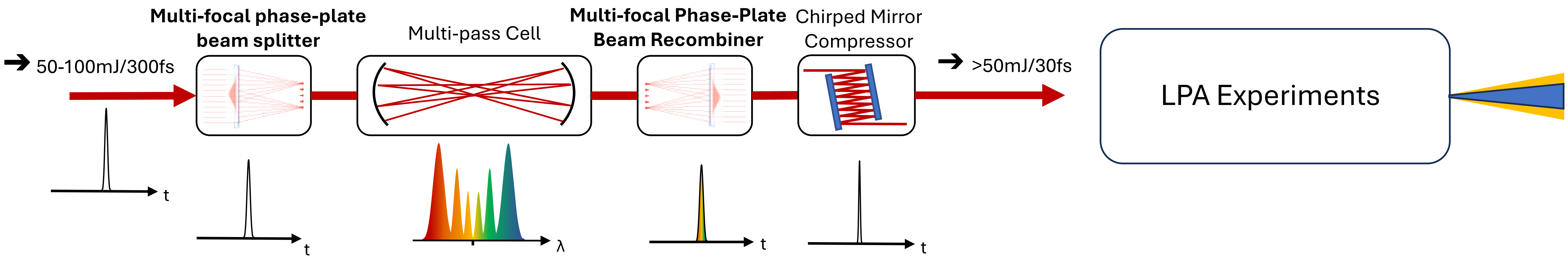
Anne-Lise Viotti, Marcus Seidel, Esmerando Escoto, Supriya Rajhans, Wim P. Leemans, Ingmar Hartl, and Christoph M. Heyl, "Multi-pass cells for post-compression of ultrashort laser pulses," Optica **9**, 197-216 (2022)
L. H. Stark, *Pulse Energy Scaling of Ultrafast Lasers via Spectral-Temporal Shaping and Coherent Combination*, doctoral dissertation, Friedrich Schiller University Jena, Jena, Germany (2025).

Coherent Beam Splitting and Recombination Based MPC Post-Compression

Multiple beams are spectrally-broadened in parallel – enabling post-compression pulse energy scaling in a compact MPC setup

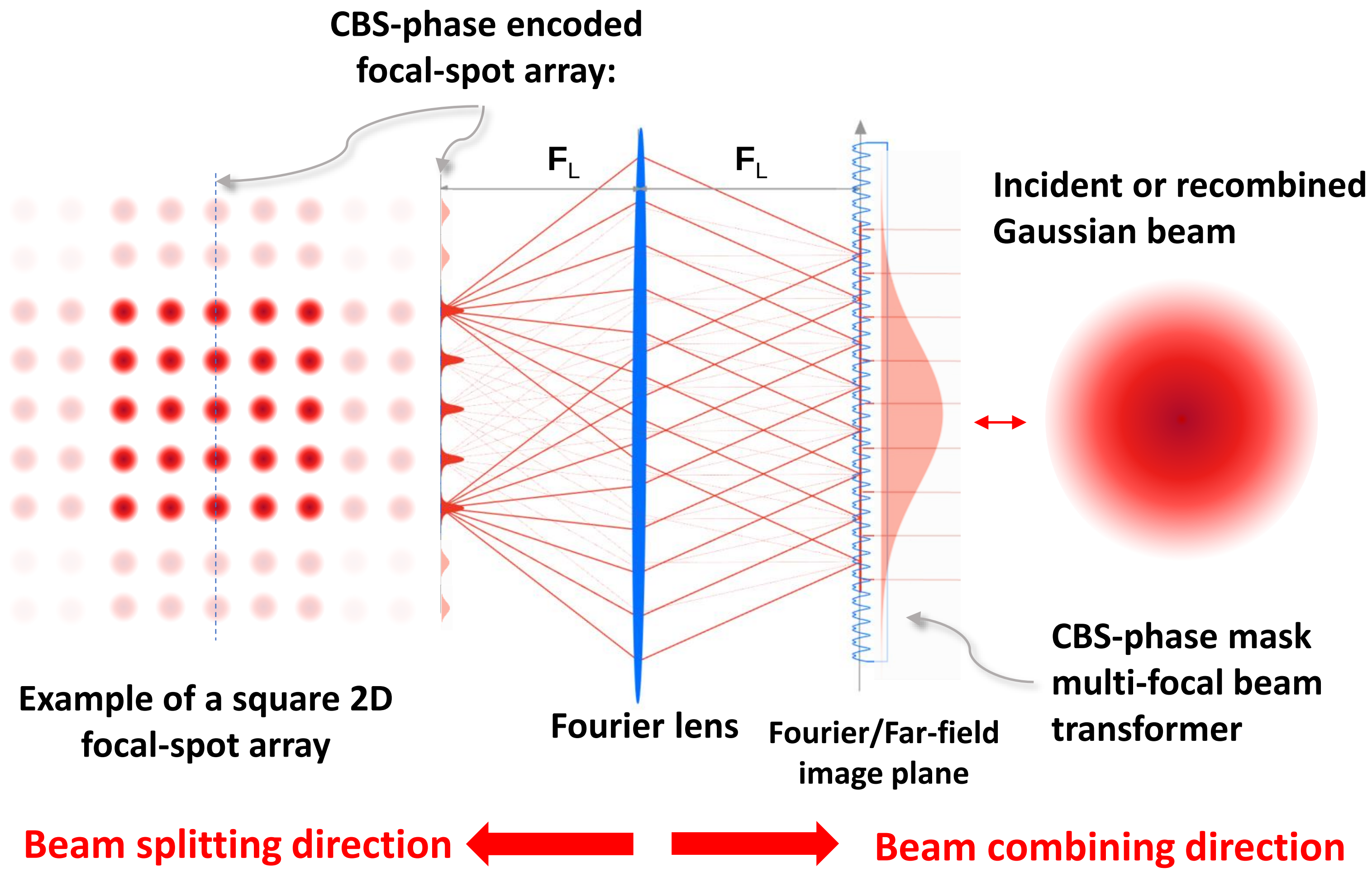
Existing coherent beam combining/splitting methods are impractical for this:
- Filled-aperture methods require individual alignment of each beam
- Tiled-aperture methods are inefficient, and cannot be used for beam splitting

To be practical, it should:
- Not require beam rephasing after spectral broadening
- Be simple to implement



Coherent Beam Stacking (CBS): A New 100% Efficient Tiled-Aperture Combining Method

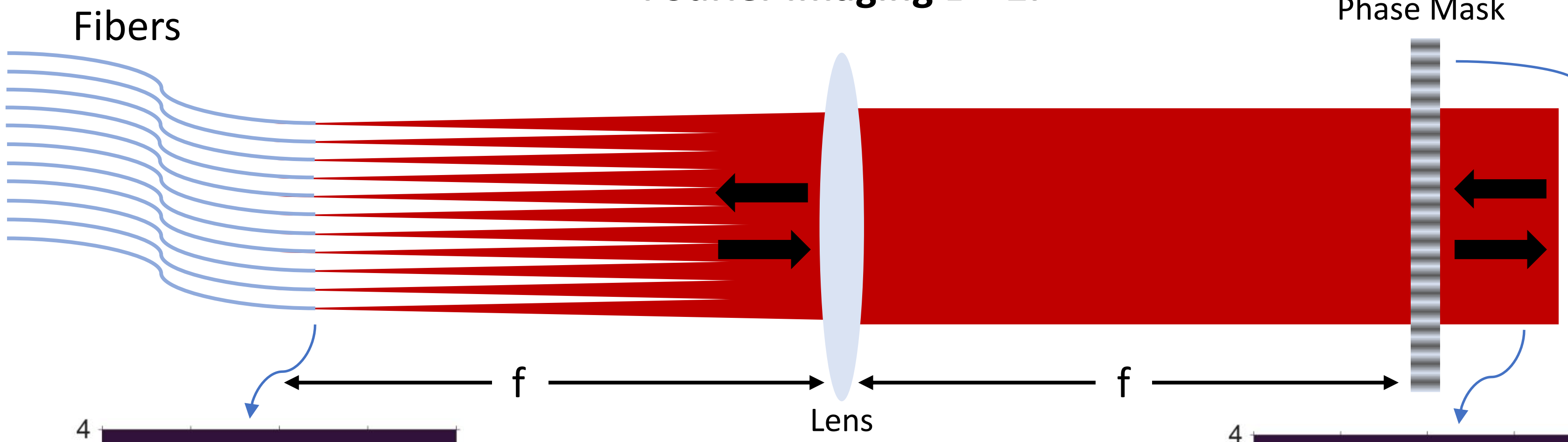
This is a Spatial-Domain Implementation of a Coherent Pulse Stacking Technique



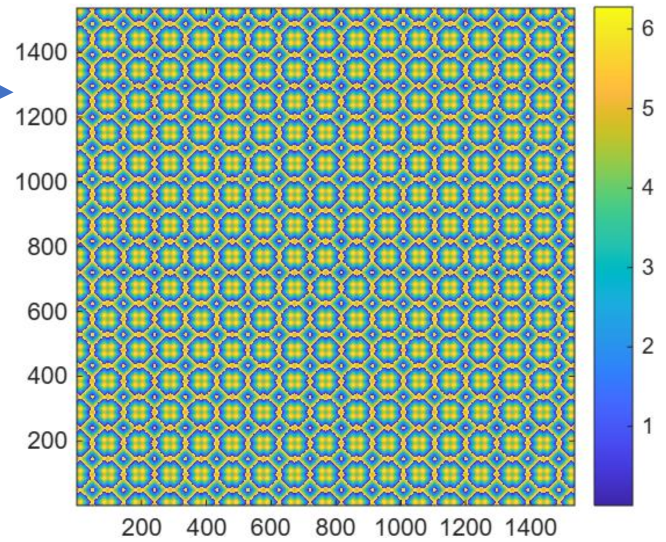
- CPS-phase encoded stacking burst is replaced by a CBS-phase encoded stacking beam array
- GTI pulse stacker is replaced by a CBS phase mask
- CBS-phase encoding erases diffraction orders, and thus enables 100% efficiency without beam-array fill-factor constraints
- Since combining occurs in a CBS phase mask, reverse propagation direction produces beam splitting
- No individual beam alignment is needed

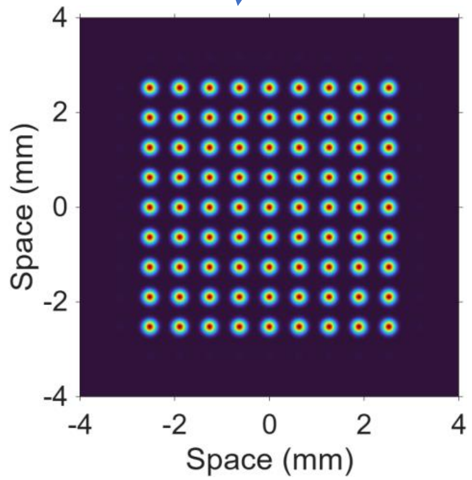
Coherent Beam Stacking has been Validated Theoretically and Numerically with Beam Propagation Methods

Fourier Imaging L = 2f

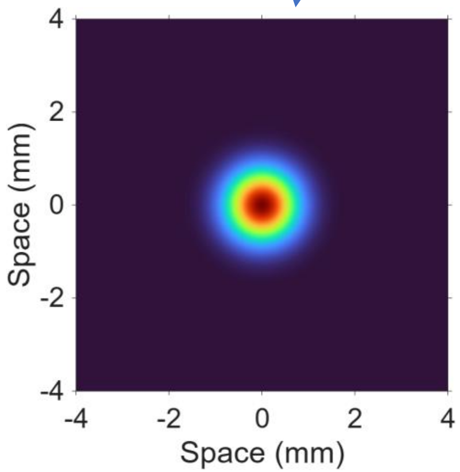


CBS phase mask combiner of the 9x9 stacking-beam array





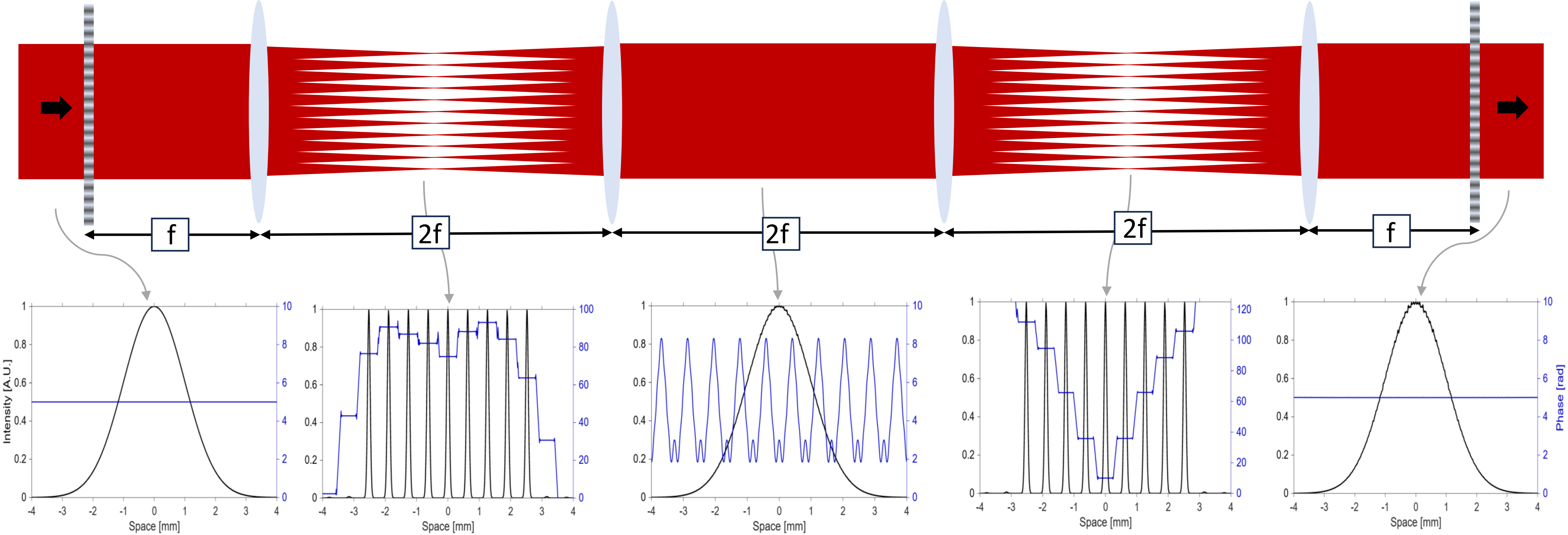
Numerically simulated stacking beam 9x9 array (from a fiber-bundle array)



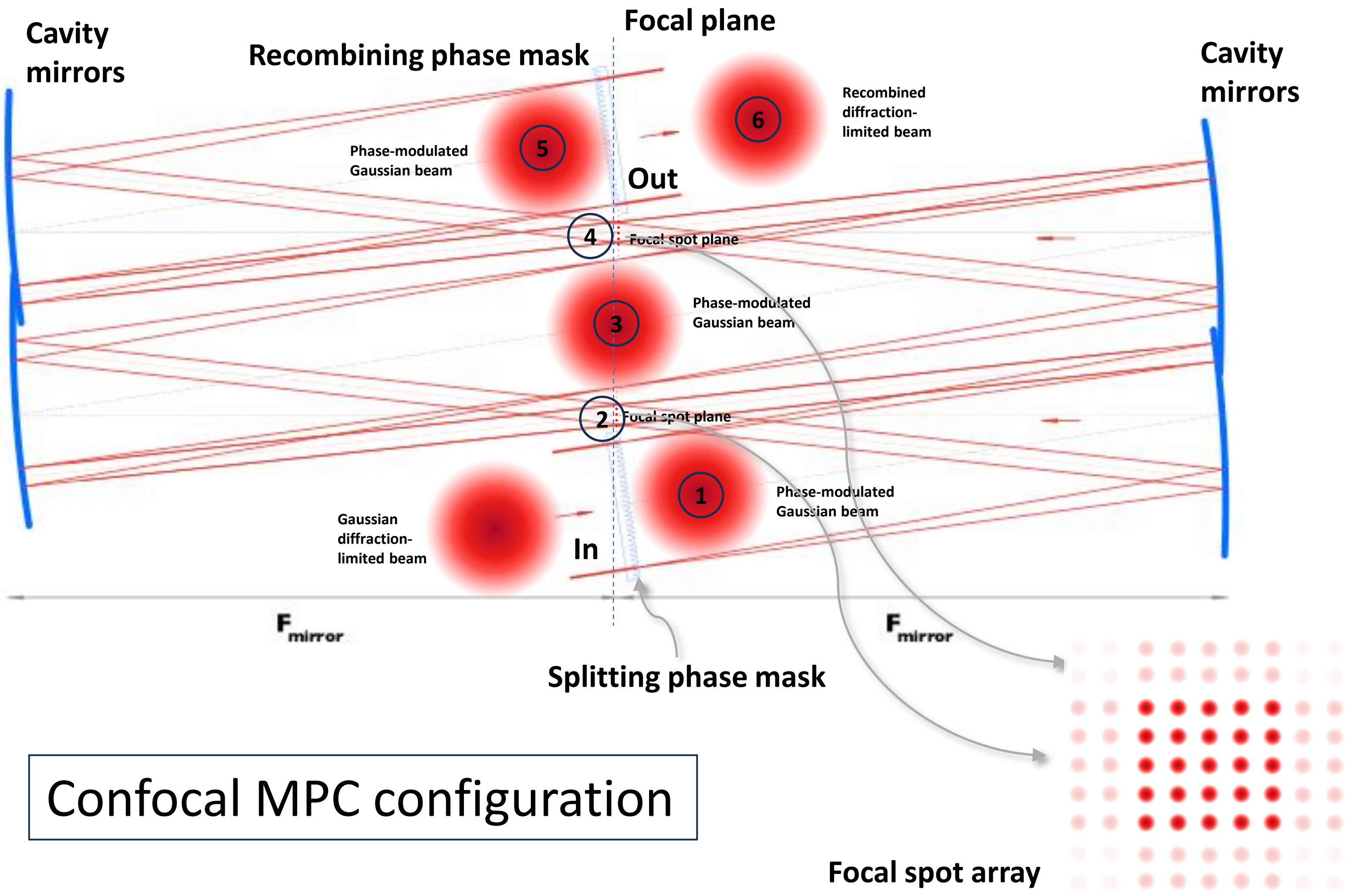
Numerically simulated combined Gaussian beam after the CBS phase mask combiner

Coherent Beam Stacking can be Implemented in Confocal Cavity Configurations

CBS can be implemented in confocal cavity configurations demonstrating simultaneous splitting and recombining



CBS Enabled Energy Scalable MPC Configuration



Confocal MPC configuration

1. Gaussian beam passes CBS phase mask positioned in the MPC focal plane, and gets transversely phase modulated
2. After FL mirror the phase-modulated Gaussian is converted into a focal-spot array in the MPC focal plane
3. After the second FL mirror phase-modulated Gaussian beam is reconstituted in the MPC focal plane
4. Step 2 is repeated again
5. Step 3 is repeated again
6. Diffraction-limited Gaussian beam reconstituted after CBS phase mask in the MPC focal plane at the output

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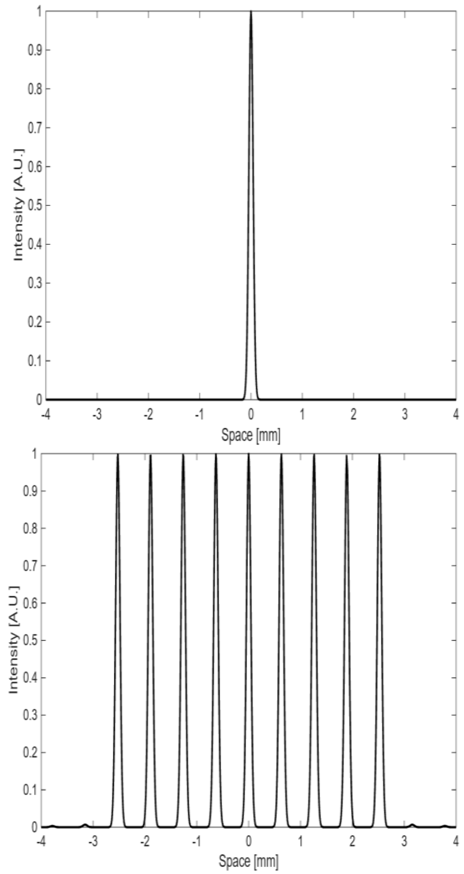
CBS Enabled Energy Scalable MPC Post-Compression Configuration

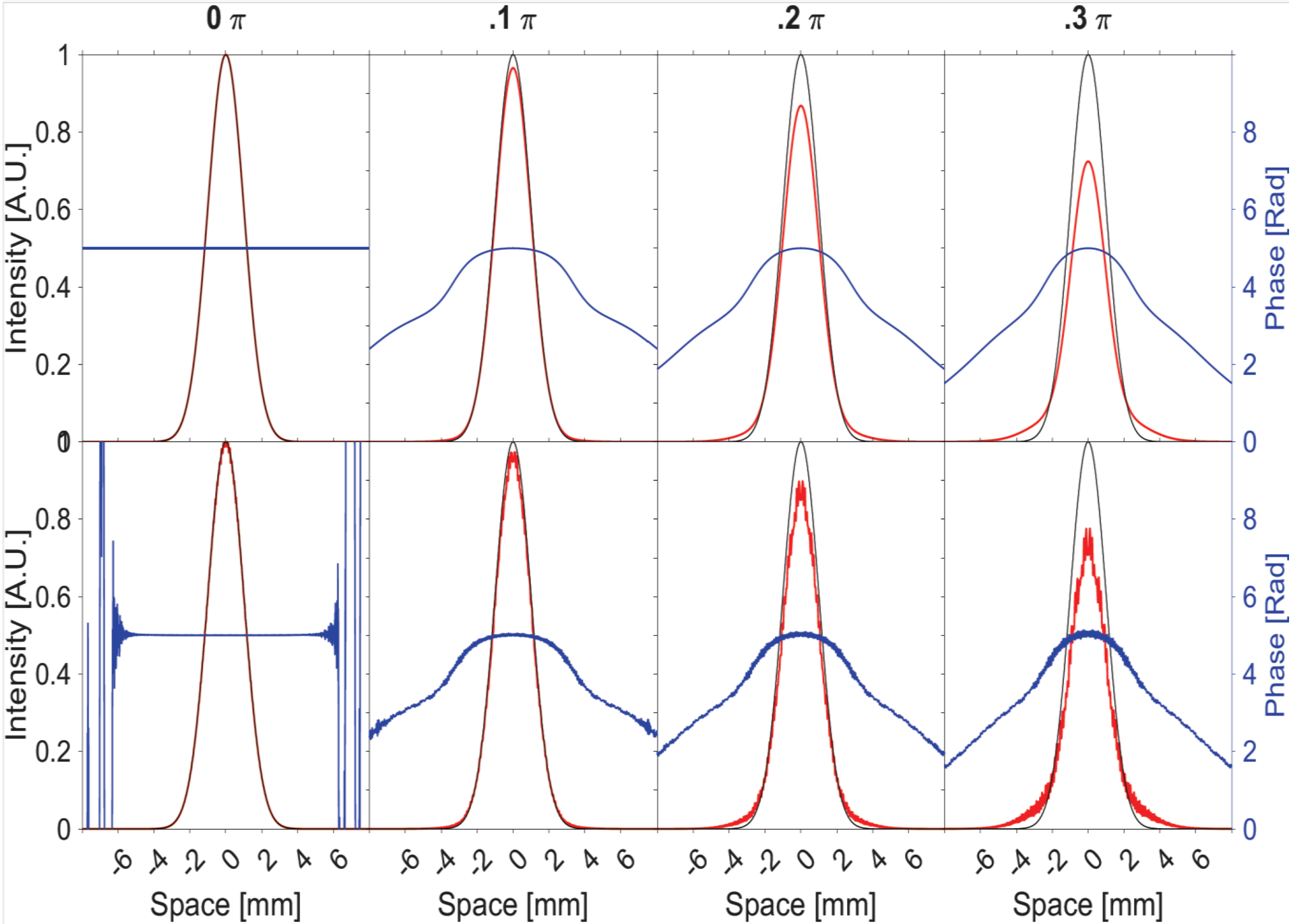
In the presence of nonlinearity, we see minimal differences when compared to standard cavity propagation

CBS Enabled Energy Scalable MPC Post-Compression Configuration: Data

We compare the response of CBS confocal to standard confocal cavities in the presence of nonlinearity

Focal Plane Field Pattern



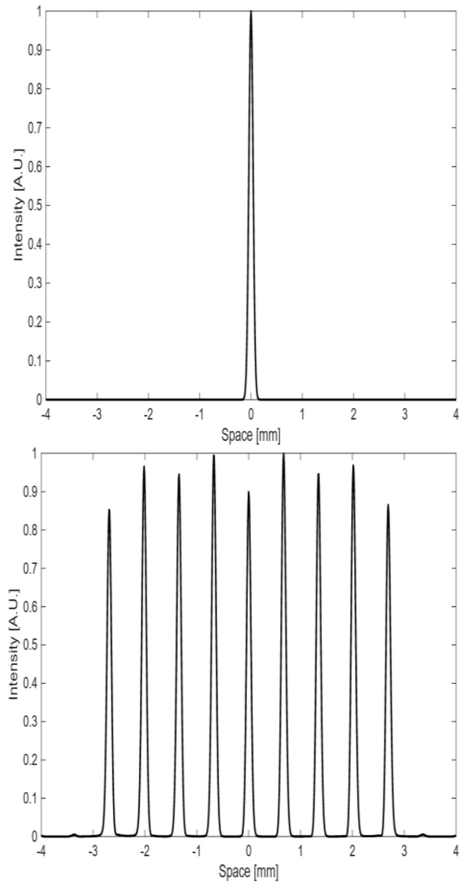


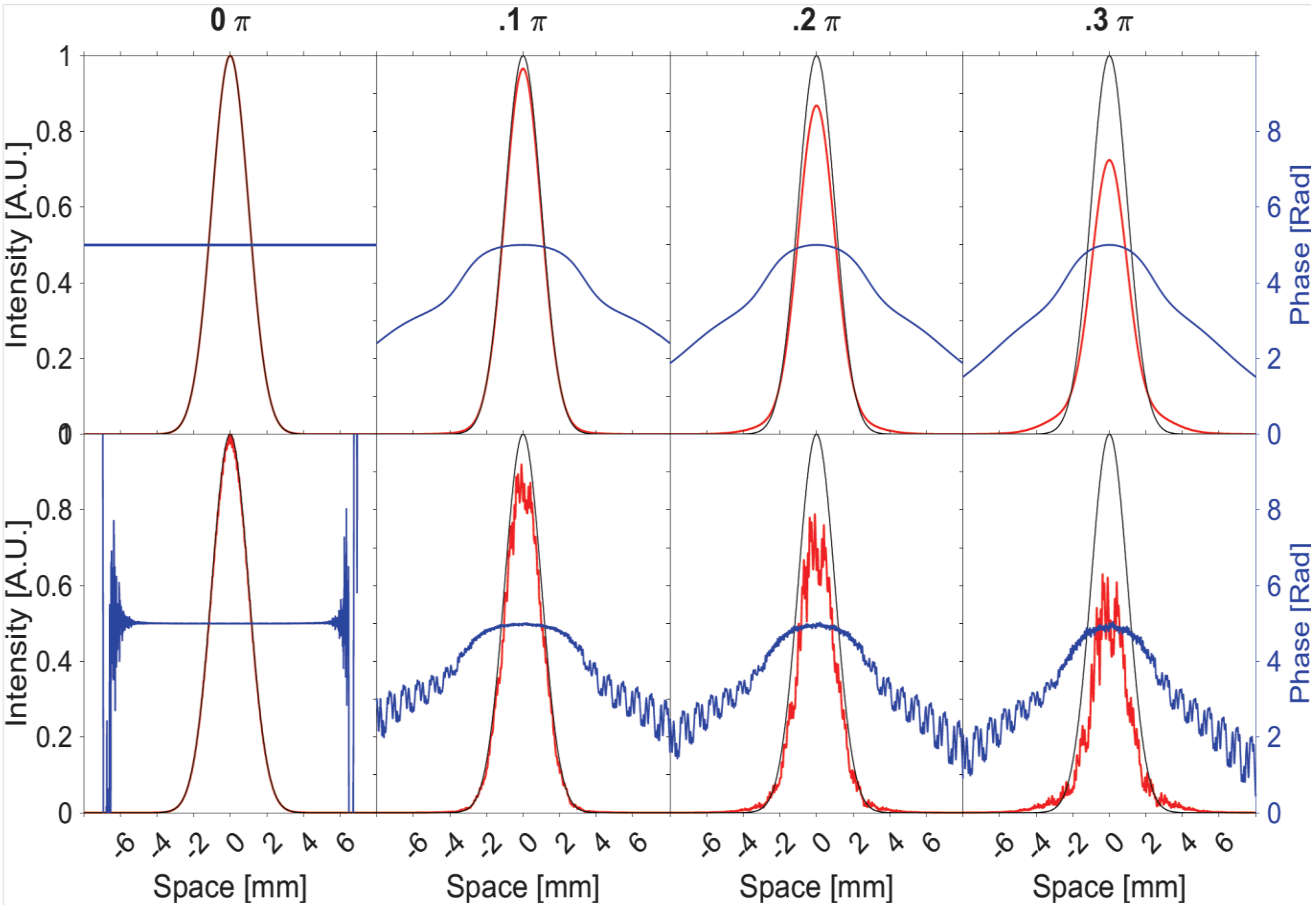
Each beam in the beam array behaves nearly identical to a single beam in the presence of nonlinearity

CBS Enabled Energy Scalable MPC Post-Compression Configuration: Data

We probe the resilience of these CBS cavities by studying the field response for unequal beam array amplitudes

Focal Plane Field Pattern





Even when beam amplitudes vary by 10-20% CBS cavities retain most single beam qualities

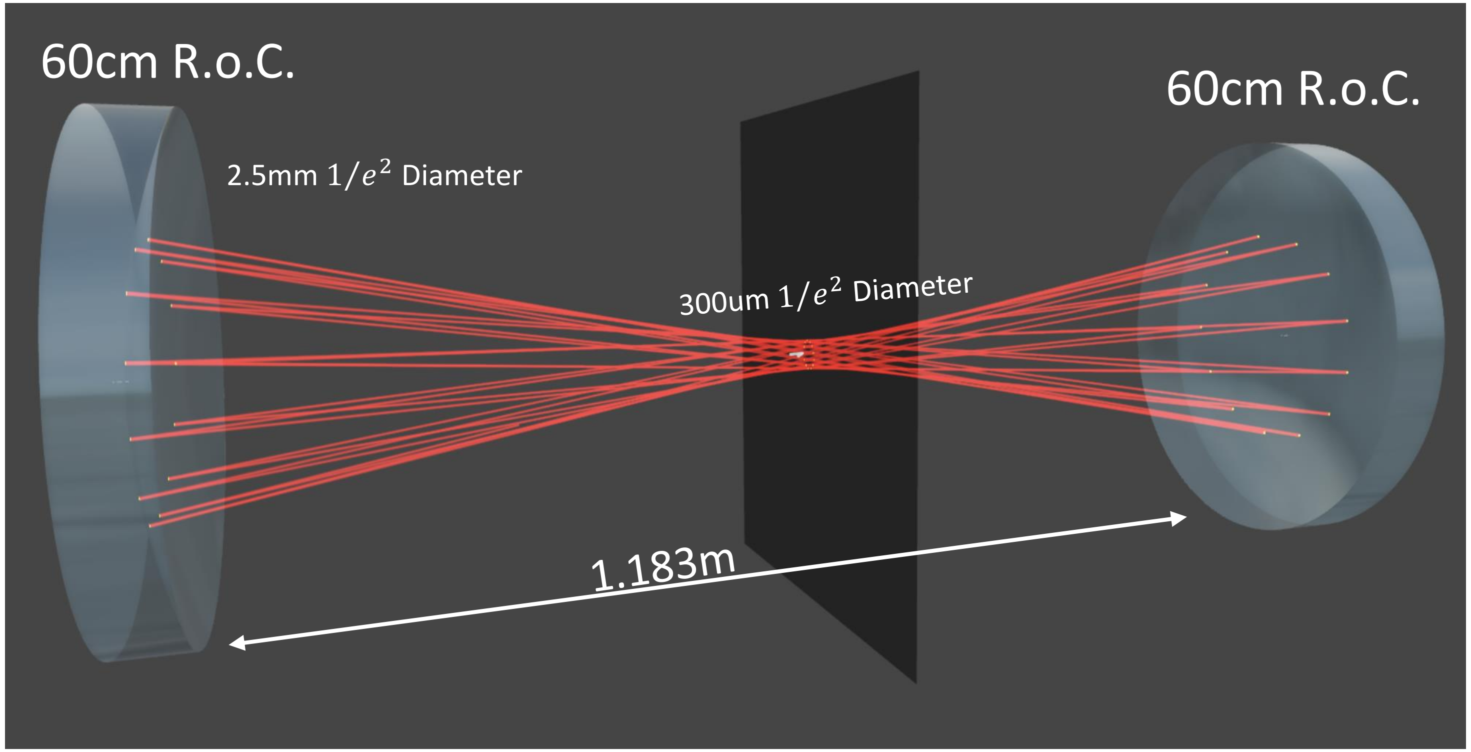
Equivalent to perturbation by $\lambda/20$

Demonstrates resilience to random perturbations: No need for active rephasing before recombination

1mJ Demonstrated Nonlinear Post-compression

Laboratory Scale 1mJ Cavities Have Been Demonstrated

- ~3.25 Total Nonlinearity Accumulated
- 98% + Spatio- Spectral Homogeneity
- 96% + Throughput Transmission
- 200fs -> 31fs

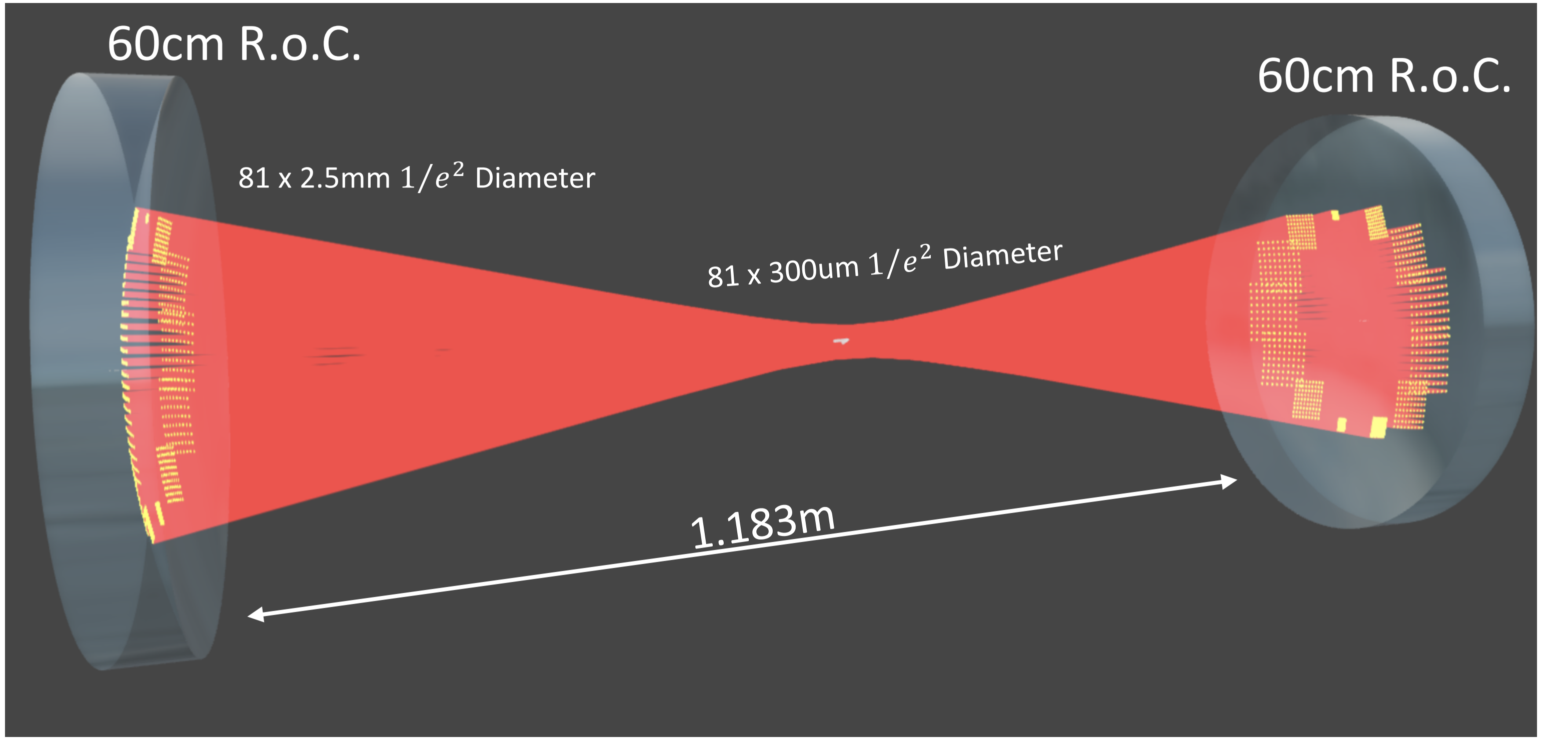


Grebing C, Müller M, Buldt J, Stark H, Limpert J. Kilowatt-average-power compression of millijoule pulses in a gas-filled multi-pass cell. Opt Lett. 2020 Nov 15;45(22):6250-6253. doi: 10.1364/OL.408998. PMID: 33186962.

CBS Enabled Energy Scalable MPC Post-Compression Configuration: Scalability

CBS can directly be applied to demonstrated compact cavities

- 81 x 1mJ
- ~4.5π Total Nonlinearity Accumulated
- 300fs -> 31fs



CBS is a pathway to joule level energies in compact cavity footprints

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Summary

- High-intensity power and energy scalable laser drivers need broader bandwidths to achieve shorter pulse durations
- CBS Post-compression as an add on to CPSA to enable an increase in bandwidth and subsequent beam stacking
- Use of Gas MPC's for highest broadening performance at high energy and average powers
- Experiment is designed for demonstrating CBS Post-compression with 81+ beams for 81 mJ spectral broadening in a 1.2m long cavity.
- CBS shows promise for scalability for joule level energies in compact footprints.

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