Development of 100mJ Coherently Combined CPSA Fiber Laser Laboratory Demonstrator for Driving Particle Acceleration and Secondary Radiation Experiments

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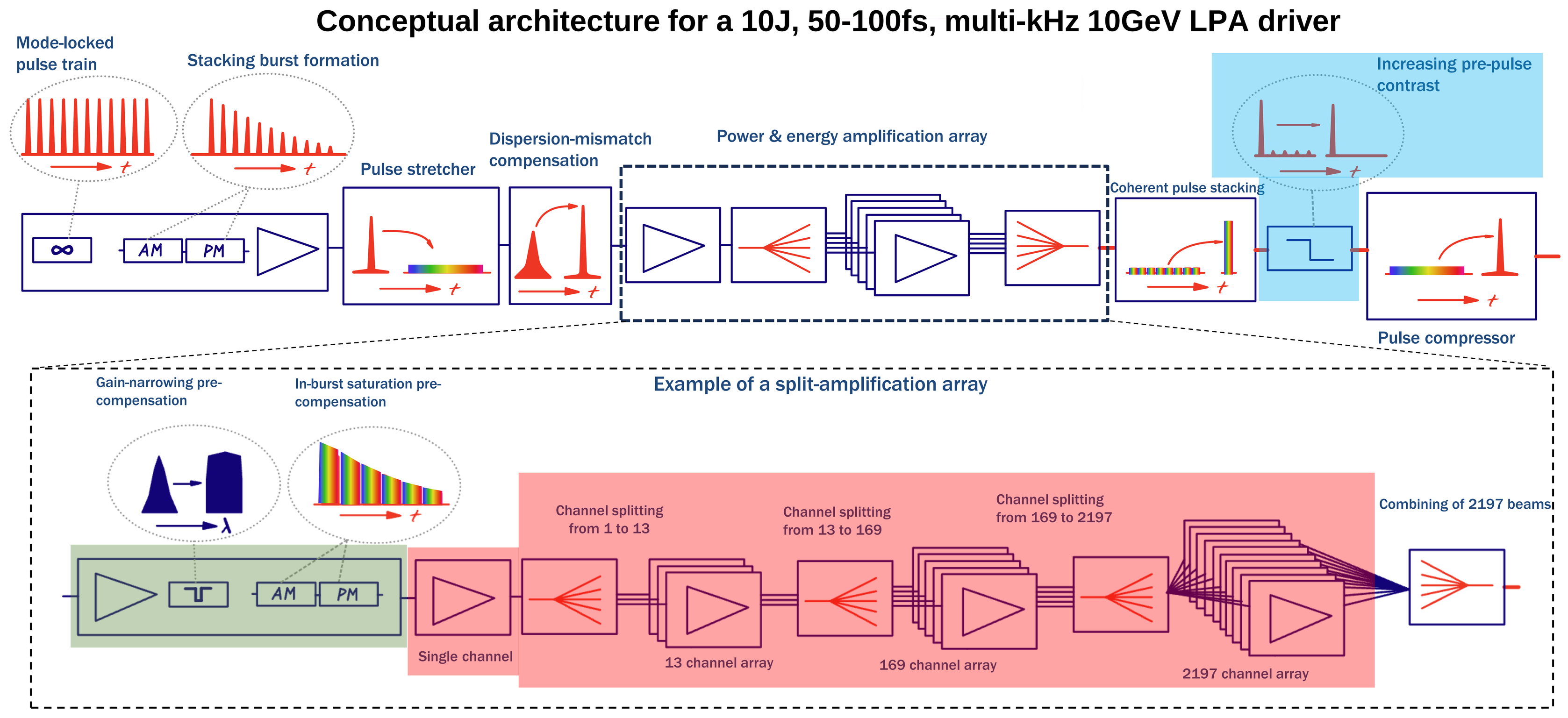
Need for High Rep. Rate Lasers

- High field science (HFS) has been enabled by high-intensity fs laser drivers at low ≤Hz rep. rates
- Next generation HFS will operate at kHz to MHz producing kWs to MW [1]
- This will require entirely new high-intensity laser technologies:
  - Coherently combined fiber lasers
  - Tm:YLF solid-state lasers
  - Yb:YAG

Fiber Lasers Offer a Path to Power / Energy Scaling

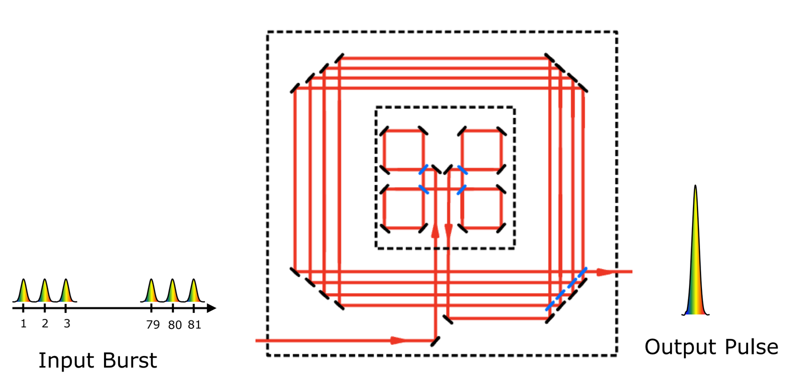
- Coherently combined fiber lasers offer:
  - ✓ Scalability to 100s of kW[2] & 1-10J
  - ✓ 30-100 fs pulses at 10-100kHz repetition rates
  - ✓ >30% wall-plug efficiency
  - ✓ Diffracted limited beam quality
  - ✓ Compactly integrated, robust and reliable laser drivers

Conceptual architecture for a 10J, 50-100fs, multi-kHz 10GeV LPA driver



Our Solution: Spatial and Temporal Coherent Combining

- Coherent Pulse Stacking Amplification (CPSA) : -Nearly full energy extraction while accruing low nonlinearity
- Gires-Tournois Interferometer (GTI) are used to temporally coherently combine fs pulses
- CPSA reduces the array size of a coherent beam combining system by **100x**!



A 4+4 multiplexed GTI system temporally combines 81 pulses into 1 output pulse

CPSA will enable 1-10 J fiber laser arrays with only ~10^2 - 10^3 fibers

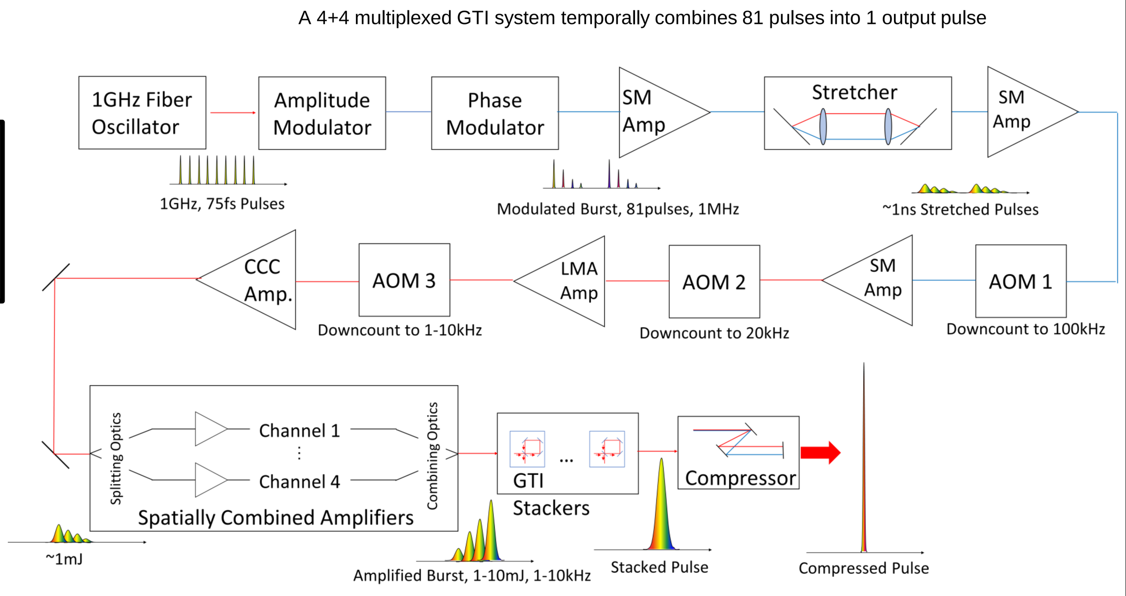
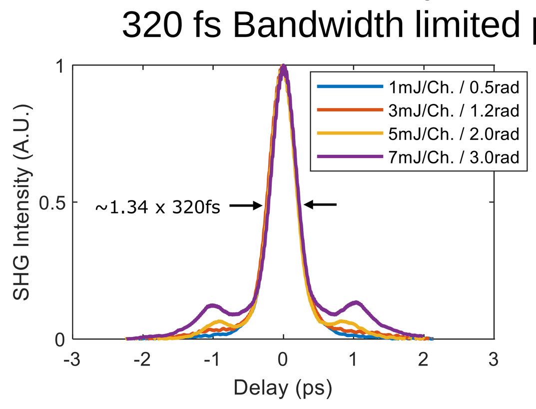
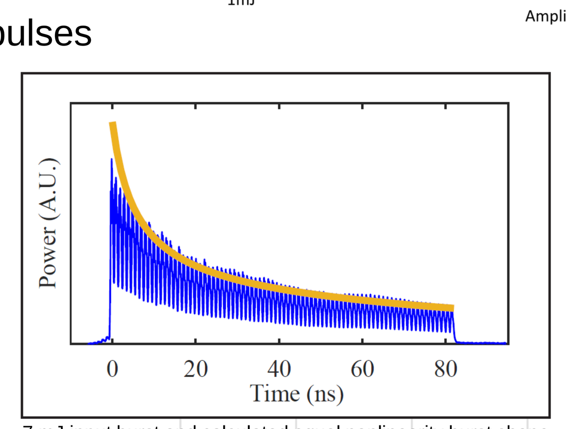


Diagram of the CPSA system

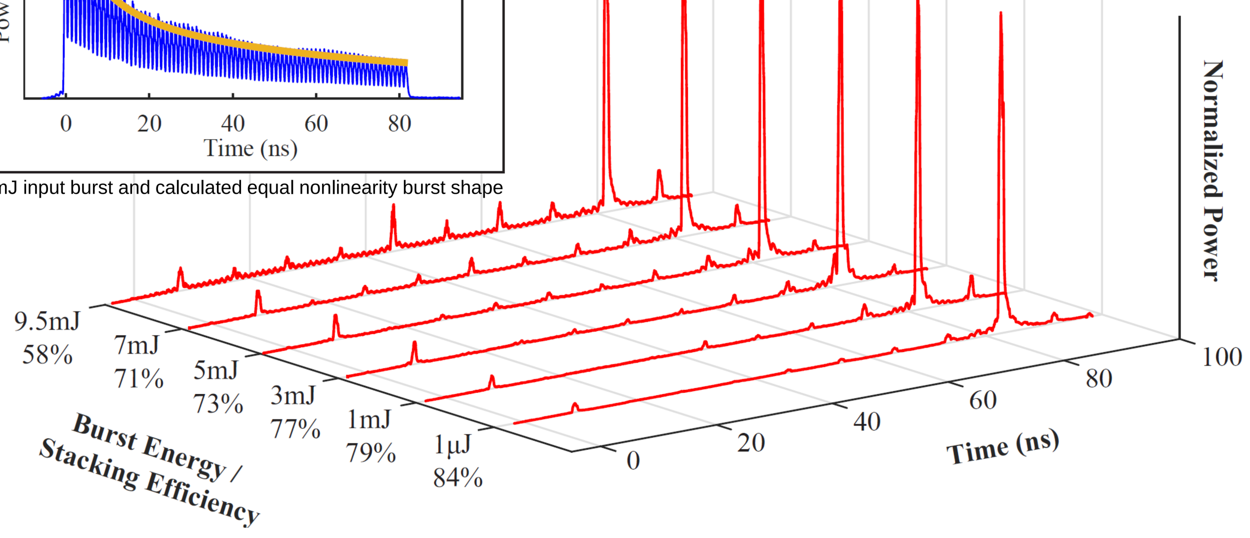
- Results:
  - ~10mJ per 85µm 3C fiber channel
  - 4 spatial channels
  - Up to 27 mJ combined energy
  - <1.4% RMS stability
  - 320 fs Bandwidth limited pulses



Measured autocorrelation traces

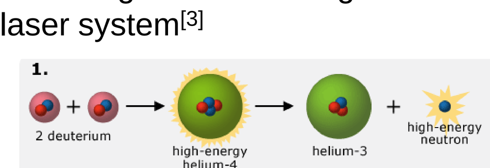


7 mJ input burst and calculated equal nonlinearity burst shape

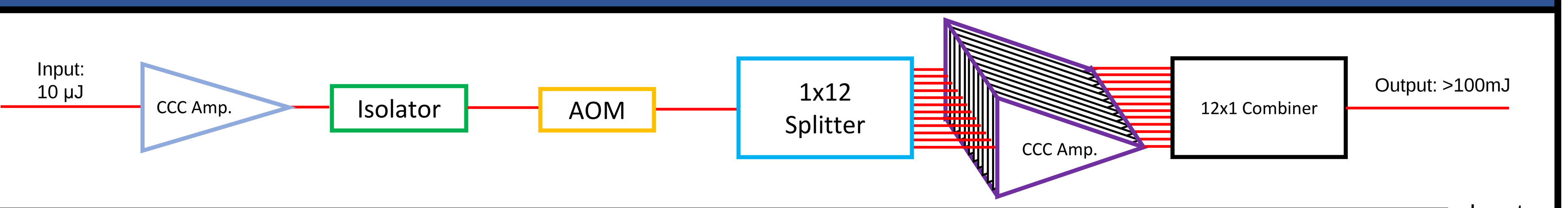


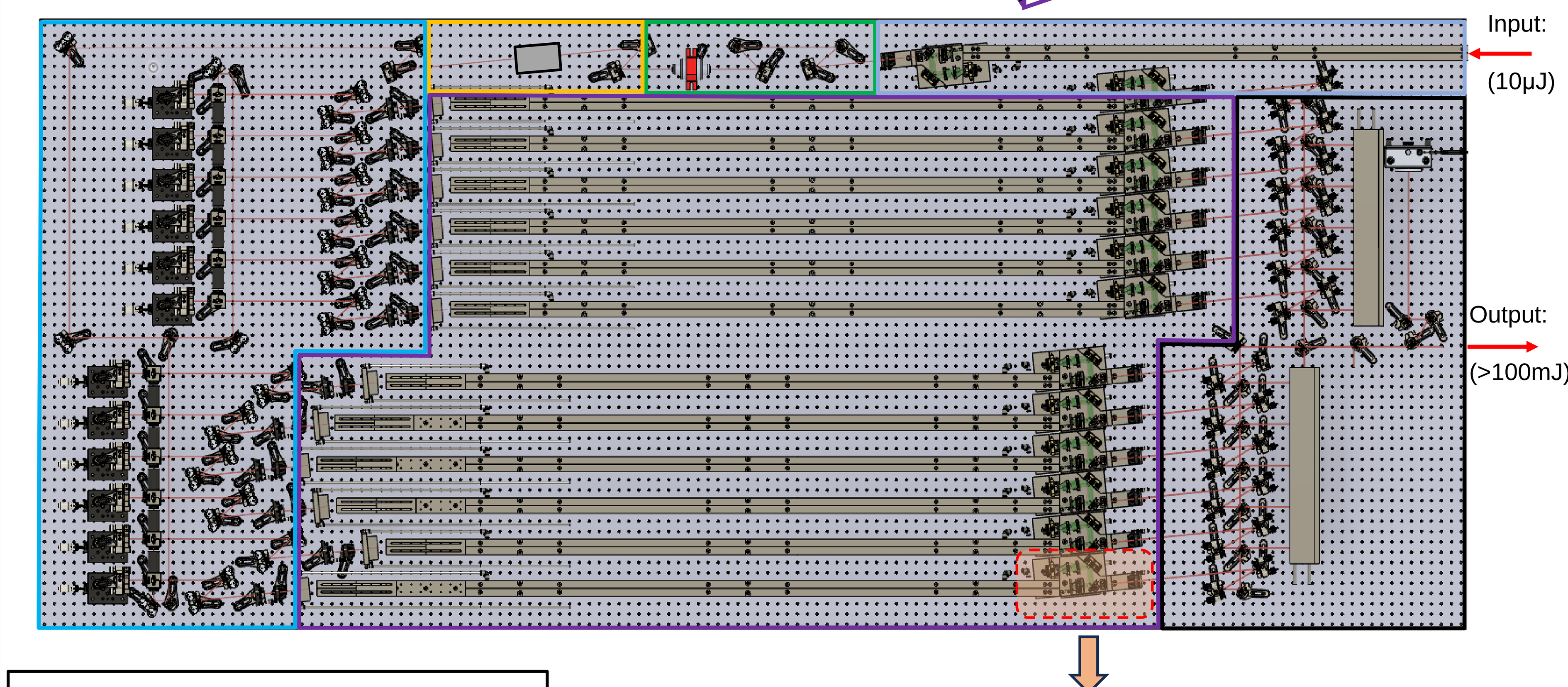
CPSA output result with different input burst energy

First Demonstration of fast neutron generation using a fiber laser system[3]

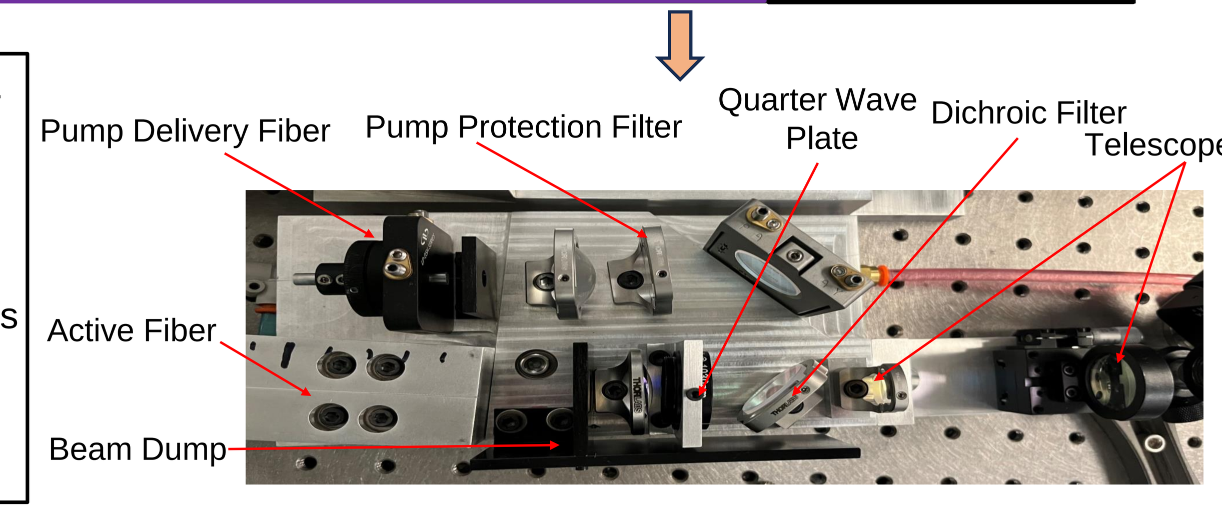


Extending CPSA Array to 12 Channels





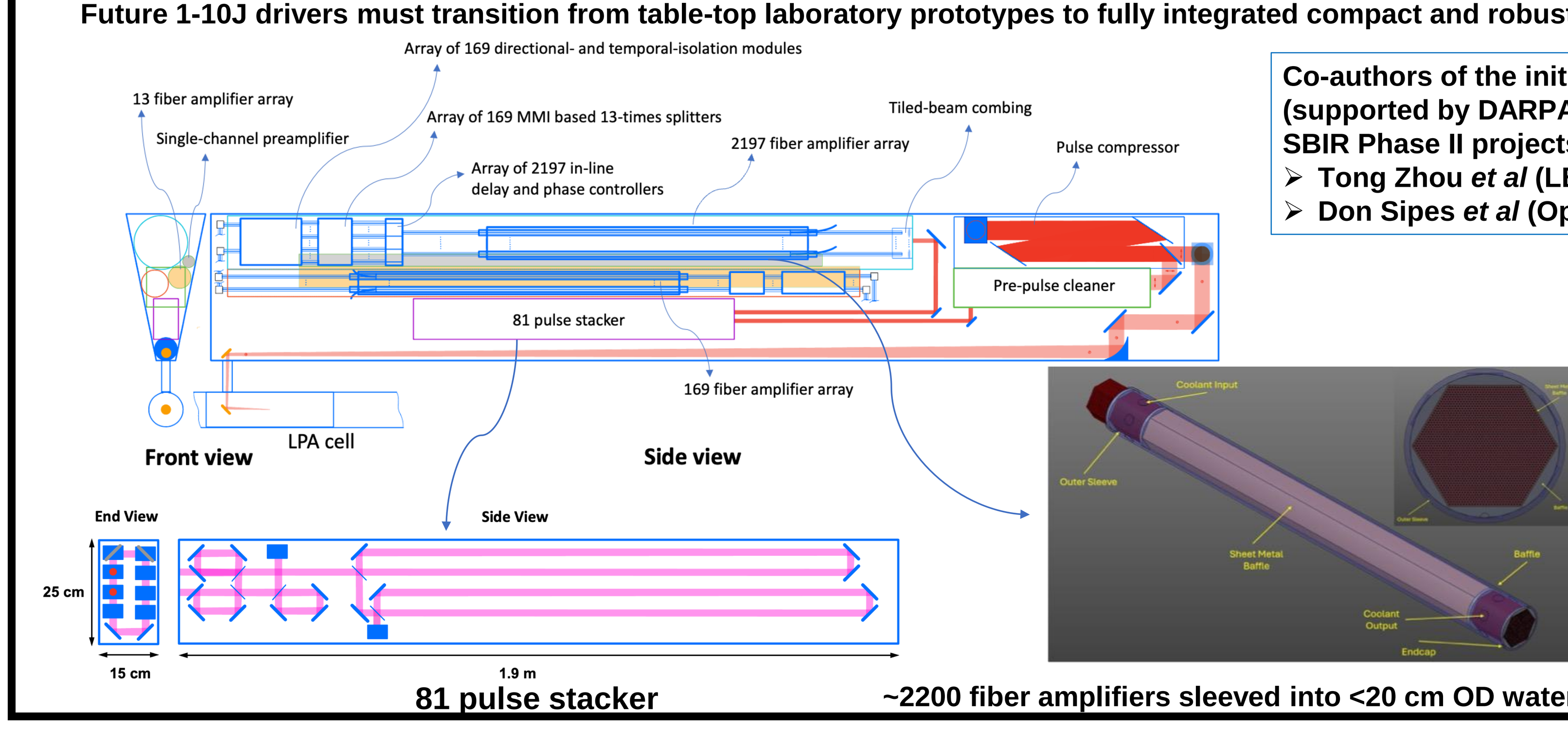
- Pursuing **100mJ** at 10kHz with 50-100 fs pulses (kW average, TW peak power)
- This 12-channels laboratory demonstrator will enable:
  - scaling neutron fluxes to ~10^7ns/s
  - Electron LPA to ~100MeV



- This 12-channel system is used to address remaining issues for large fiber arrays:
  - Management of nonlinear phase accrued over sequential split-amplification stages
  - Gain-narrowing compensation and in-burst saturation control for achieving 50-100fs pulses
  - Achieving sufficient pre-pulse contrasts for pursuing HIS

Initial Design Study for a 10-GeV LPA Fiber Laser Driver

Future 1-10J drivers must transition from table-top laboratory prototypes to fully integrated compact and robust laser systems:



81 pulse stacker **~2200 fiber amplifiers sleeved into <20 cm OD water-cooled tube**

Co-authors of the initial design study: (supported by DARPA MuS2, and DOE SBIR Phase II projects)
- **Tong Zhou *et al* (LBNL)**
- **Don Sipes *et al* (Optical Engines)**

Summary and Ongoing Work

- Fiber lasers offer an efficient, scalable path to 100's of kW ultrafast lasers with 1-10J per pulse
- CPSA achieved stable and efficient spatial and temporal combining at ~10 mJ energies with femtosecond pulses; Demonstrated the first fast neutron generation using a fiber laser system
- Scaling CPSA system to 12 channels/100mJ/10kHz at the University of Michigan
- Spectrally combined 200mJ system is under construction at Berkeley National Lab supported by DOE ECRP and Moore Foundation Funding
- Conceptual system design work is being carried out under DARPA MuS2 program to validate feasibility of compact and robust coherently-combined fiber laser drivers

Acknowledgements and References

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Pump diodes are provided by nLight Inc.; CCC fibers are fabricated at nLight Inc.

[1] https://science.osti.gov/-/media/ardap/pdf/2024/Laser-Technology-Workshop-Report_20240105_final.pdf.
[2] Karr, Thomas, and James Trebes. "The new laser weapons." *Physics Today* 77.1 (2024): 32-38.
[3] https://undsci.berkeley.edu/teach-resources/products-of-deuterium-fusion