High average power ultrafast laser technologies for driving future advanced accelerators   LOI Snowmass #221

Advanced laser technologies are needed to achieve the acceleration energies/gradients that make LPA attractive

- Pushing to TeV, repetition rates will be important (He 2015)
- Better particle beam characteristics: energy spread
- Colliders

Goal: "The vast majority of applications relevant to the DOE and other agencies require average powers and rep rates higher than the present state of the art by, in some cases, more than a factor of 1000." –kBELLA workshop report

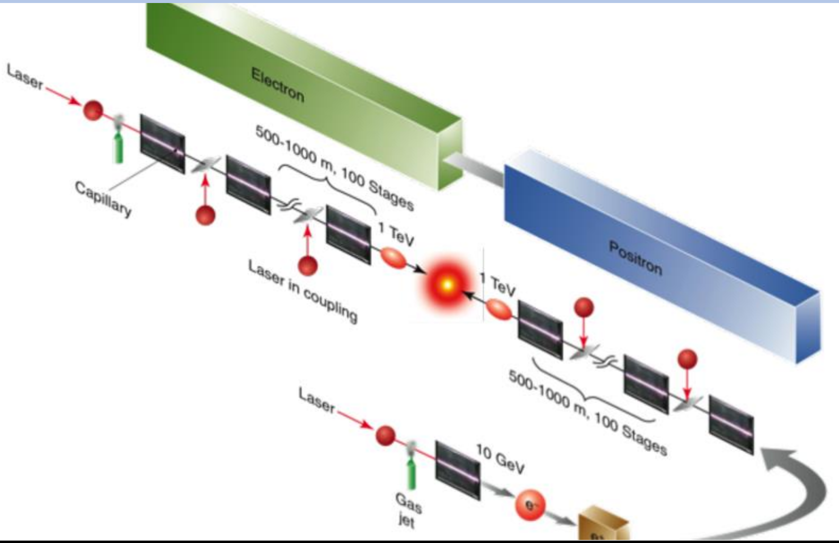
- high peak power (of order 10 J in 100 fs)
- high average power (tens of kHz repetition rate)
- high efficiency (wall-to-target efficiency of tens of percent)

Several techniques have been proposed to achieve these goals, but all need sustained R&D to reach technical readiness as LPA drivers

Laser technology development is required in parallel with accelerator development

Broad participation: DoE national labs, global research centers, universities and private-sector companies

TeV colliders



Scaling down facility sizes

2019: 8 GeV record in a 20 cm plasma

vs. 300-500m conventional

W. Leemans and E. Esarey. "Laser-driven plasma-wave electron accelerators." Phys. Today 62, no. 3 (2009).

A. J. Gonsalves, K. Nakamura, J. Daniels, C. Benedetti, C. Pieronek, T. C. H. De Raadt, S. Steinke et al. "Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide." Physical review letters 122, no. 8 (2019).Report of Workshop on Laser Technology for k-BELLA and Beyond, (May 9-11, 2017);

R. Falcone, F. Albert, F. Beg, S. Glenzer, T. Ditmire, T. Spinka, and J. Zuegel. "Workshop Report: Brightest Light Initiative (March 27-29 2019, OSA Headquarters, Washington, DC)." *arXiv preprint arXiv:2002.09712* (2020).

Z. H. He, B. Hou, V. Lebailly, J. A. Nees, K. Krushelnick, and A. G. R. Thomas, "Coherent control of plasma dynamics." Nature communications 6, 1-7 (2015).

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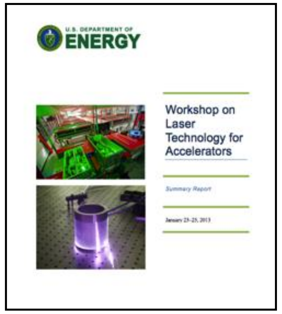
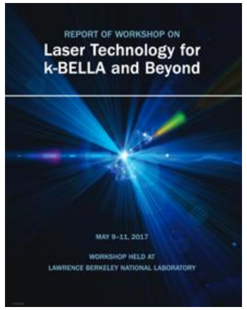
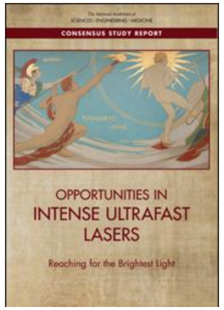
Workshops advancing laser technology







Collaborations and engagements:

Laser operations – SLAC, UR LLE

Laser shaping and control – UR LLE

Efficient future technologies – HEP Stewardship with U.M., LBNL, LLNL, nLight, Optical Engines

kHz compression – LLNL and UR LLE

Pump lasers – Coherent, Northrop Grumman, Colorado State, MIT-LL

Coatings – OSU, Colorado State

Laser energy scaling will require ongoing research in laser architectures, novel materials, optics and techniques to support laser systems that exceed today's limitations

Investment in diode pumped solid state lasers

- Gain materials and laser architectures at kHz rep rates
- Power handling optics
- Active controls

Increasing laser energy alone does not enable applications

Precision laser shaping and control required for LPA quality and efficiency

- Laser pointing: from μrad to < 0.1 μrad
- Focal spot/wave front: now at fluct. limit
- Near field: currently not well controlled
- Pulse shape, carrier envelope phase...

A kHz laser capability is crucial to advance on the LPA roadmap and for high impact applications

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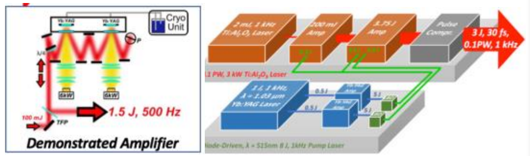
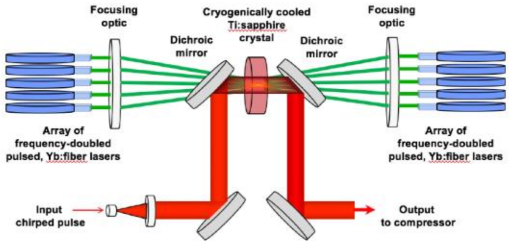
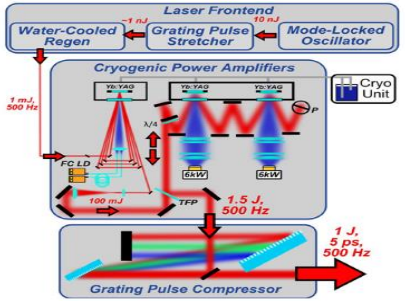
Ti:Sa

New pumping schemes

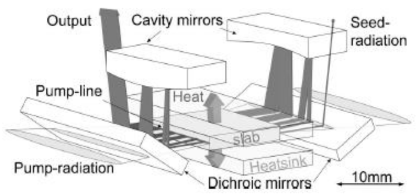




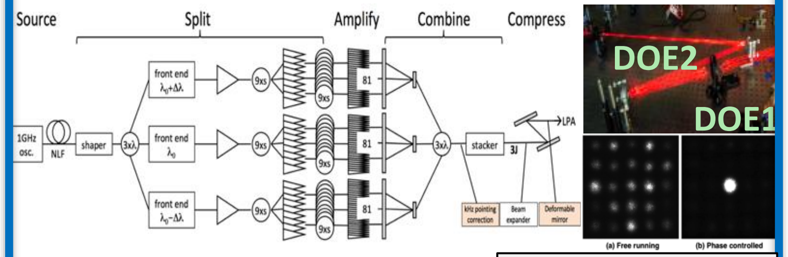
Cryo-cooled Yb:YAG



Innoslab

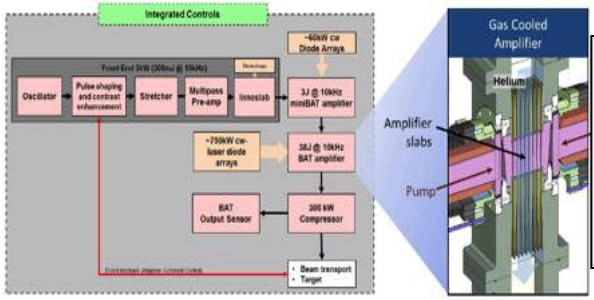


Fiber lasers



~100 fibers x 100 pulses

Tm:YLF

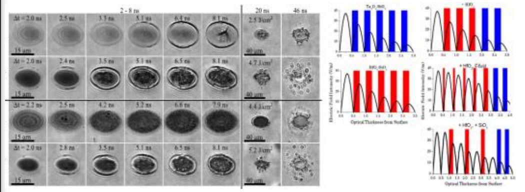


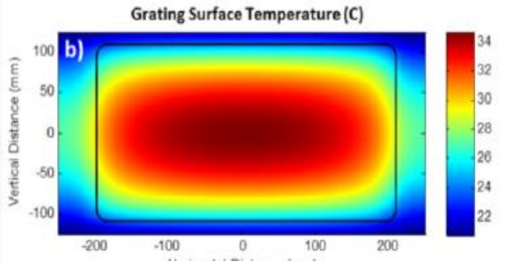
Direct diode pump,

low quantum defect

Optics at high average power: coatings, cooling, adaptive controls

Scaling optics damage thresholds





Near-term kHz –Ti:Sa is ready with new pumping concepts and could possibly scale to 10 kW range.
Mid-term and long term – Fiber, Tm:YLF, Innoslab Yb:YAG or Tm:YLF, Cryo-cooled Yb:YAG.
Development of high peak and high average power handling gratings and optics will be needed as well.

N. Talisa, A. Alshafey, M. Tripepi, J. Krebs, A. Davenport, E. Randel, C. Menoni, and E. Chowdhury, "Comparison of damage and ablation dynamics of multilayer dielectric films initiated by few-cycle pulses versus longer femtosecond pulses," Opt. Lett. **45**, 2672-2675 (2020)

D. Schiltz, D. Patel, C. Baumgarten, B. Reagan, J. Rocca, and C. Menoni, "Strategies to increase laser damage performance of Ta_2O_5/SiO_2 mirrors by modifications of the top layer design," Appl. Opt. **56**, C136-C139 (2017)

D. A. Alessi, P. A. Rosso, H. T. Nguyen, M. D. Aasen, J. A. Britten, and C. Haefner, "Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers," Opt. Express 24, 30015 (2016)

Value of a demonstrator facility is threefold:

(1) develop and demonstrate the laser technology needed to drive a 1-GeV, 1-kHz LPA

(2) develop know-how in handling high average power ultrafast lasers and LPA technology, including power handling systems, feedback controls and high repetition rate operations/data acquisition and

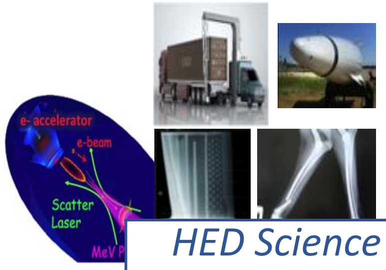
(3) develop, optimize and utilize a 1 GeV, 1 kHz LPA facility for a wide variety of experiments on science and applications relevant to DOE and other agencies

Near term applications: radiation sources and ultrafast science, as well as laser-based machining

Mid and long term applications: chemical, condensed matter or biological experiments at the new generation of high-repetition-rate free-electron lasers and synchrotrons

Eventually would enable an LPA based collider at the 10-100kW range

Industry and Medical X-ray Characterization



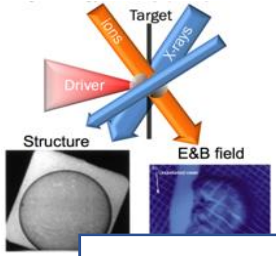
Precision

Mono-Energy

High res.

Remote sensing

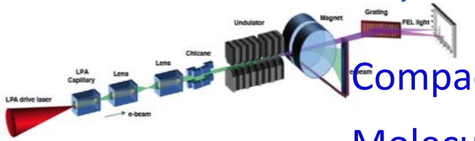
HED Science NIH/NCI Oncology



Precision probes/pumps

New therapy sources

Basic Science. Industry Coherent X-rays

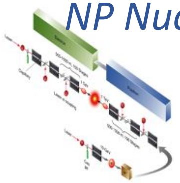


Compact FELs

Molecular dynamics

Microelectronics

HEP Future Particle Colliders
NP Nuclear Science



Extend energy frontier

Access exotic nuclear states

Demonstrator facility is an important and cost-effective next step that will provide a way to investigate challenges and advance the path towards applications.