22th ATF User Meeting

December 3-5, 2019

# Combined Laser-Electron Beam Capabilities and Plan

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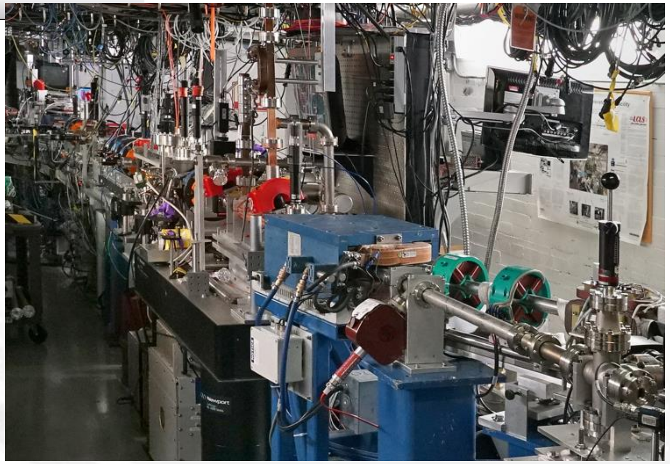
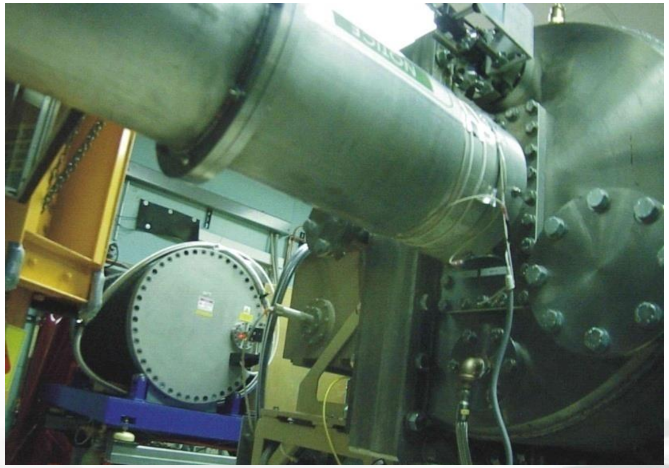
U.S. DEPARTMENT OF ENERGY

# from Scientific Needs Workshop 2017 Report:


*"The $CO_2$ laser has a longer wavelength than lasers at other advanced accelerator facilities. This leads to the ability to perform different, and often better diagnosed, LPA and other laser-beam experiments."*

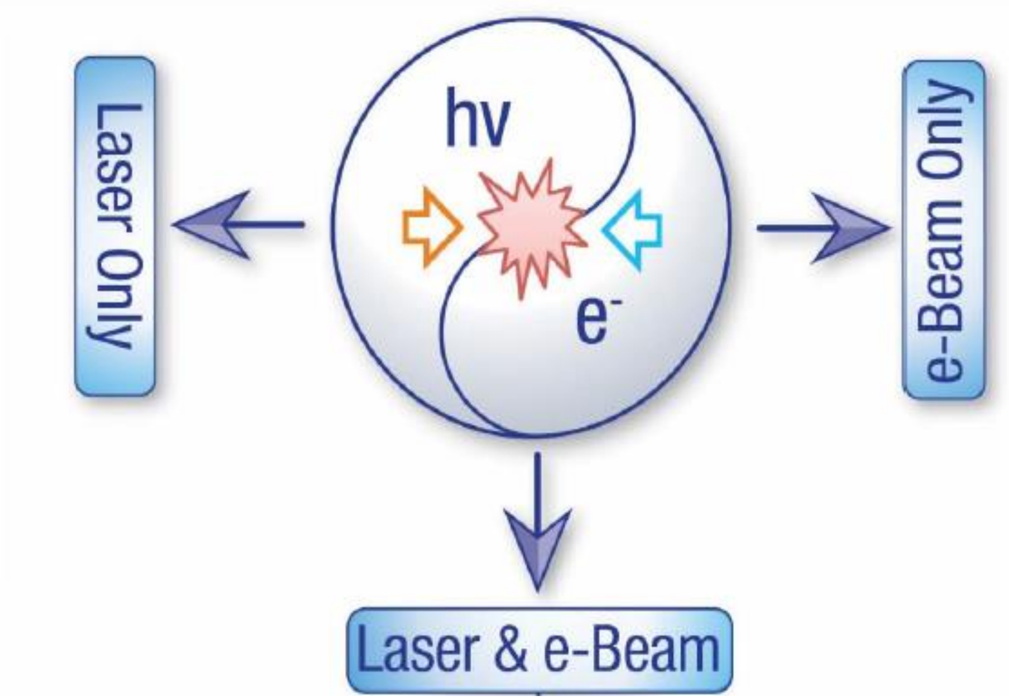
*"The co-location of a high-brightness electron beam and a TW-scale picosecond laser is unique and enables experiments that cannot be done at other DOE/SC/HEP facilities such as BELLA, AWA, or FACET-II."*





# Multiple and combined tools are in demand by ATF users

AE66; AE85;
AE89; AE92
+3 new proposals




AE62; AE63;
AE68; AE90
+3 new proposals

AE76; AE77; AE86; AE87; AE88; AF90; AE93; AE95 +3 new proposals

*Co-propagation:* electron acceleration (new mechanisms, injection, staging, fields mapping)

*Counter-propagation:* radiation sources (ICS, plasma FEL)

*Cross-propagation:* fields probing

# Active ATF Laser Experiments

- AE66 - Modification of Gas Jet Density Profile with Hydrodynamic Shocks for CO2 Laser Ion Acceleration Experiment, NRL/Imperial College
- ✓ AE76 - High Duty Cycle FEL, Radiabeam
- ✓ AE77 - Advanced IFEL, UCLA
- AE85 - Multiatmospheric CO2 Amplifier Optically Pumped by a 4.3 micron FeZnSe Laser, UCLA
- ✓ AE86 - Plasma Ion Channel Undulator (PICU) using Electron Beam in CO2 Laser-Driven Channel, ICL
- ✓ AE87 - Hard X-ray ICS, UCLA
- ✓ AE88 - Electron Beam Formation via Ionization Injection for Next Generation Accelerator R&D, BNL
- AE89 - Plasma Compression for Terawatt Long Wavelength Lasers, NRL
- ✓ AF90 - Plasma Beam Dump Feasibility Study, UC-Denver
- AE92 - Clearing a Path Through Fog Droplets using a Short-Pulse (sub-nsec) CO2 Laser, NRL
- ✓ AE93 - Direct Measurment of Fields and Radiation in the Self-Modulated Plasma Wakefield Regime, SUNY-SB
- ✓ AE95 - Optical Diagnosis of Self-Modulated CO2-laser Driven Plasma Wakes, UT-Austin

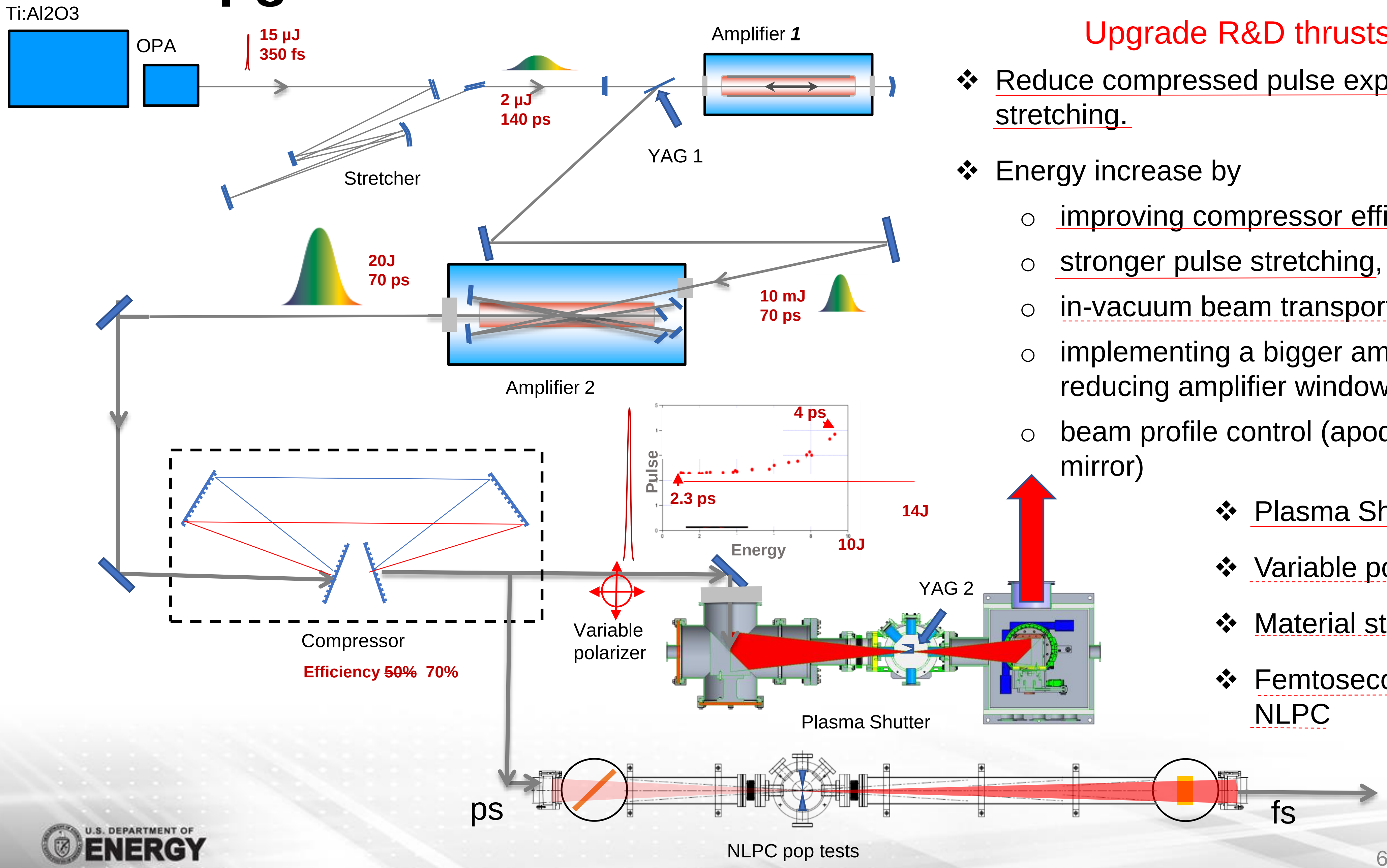
✓ Marked red experiments use $CO_2$ laser combined with electron beam (8 out of 12)

# from Scientific Needs Workshop 2017 Report:


## Priority Research Directions:

| PRD | Requirement |
|---|---|
| Nonlinear Kerr effect | 1-10 TW |
| Non-linear LWFA | ~2 TW |
| Blow-out LWFA | 5-10 TW, 0.5 ps |
| Bubble LWFA | 25-30 TW, 0.5 ps |
| Ion acceleration | 25-100 TW, circ. polar |
| IFEL | 25-100 TW |
| DLA | 10-100 GW |
| ICS | 2-10 TW |

# Laser upgrades – December 2019 status

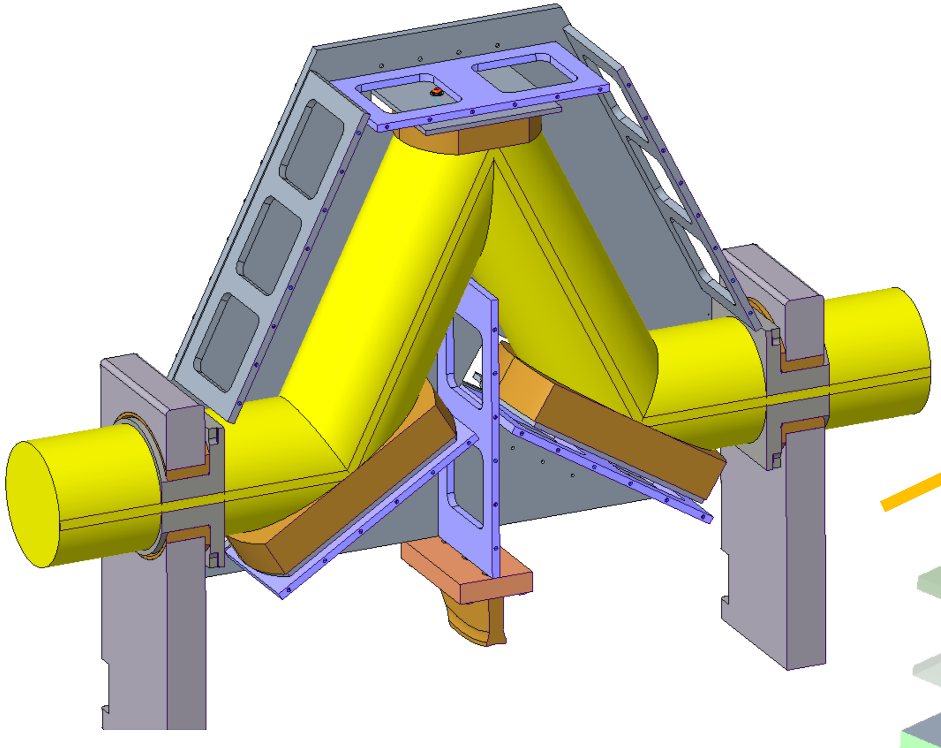


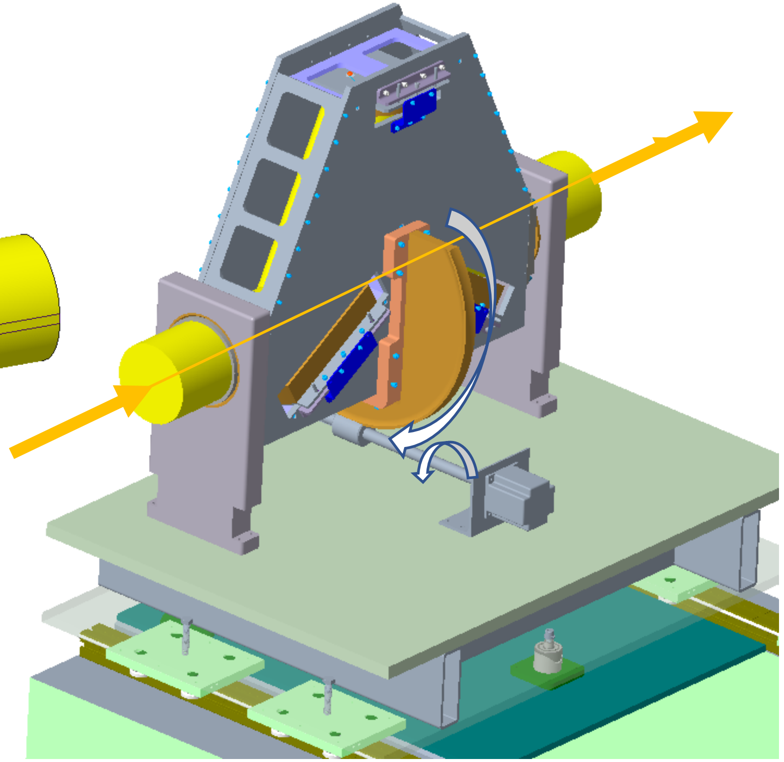

## Upgrade R&D thrusts:

- Reduce compressed pulse expansion via stronger stretching.
- Energy increase by
  - improving compressor efficiency,
  - stronger pulse stretching,
  - in-vacuum beam transport
  - implementing a bigger amplifier and window, reducing amplifier window thickness,
  - beam profile control (apodizing, adaptive mirror)
- Plasma Shutter
- Variable polarization
- Material studies
- Femtosecond regime with NLPC

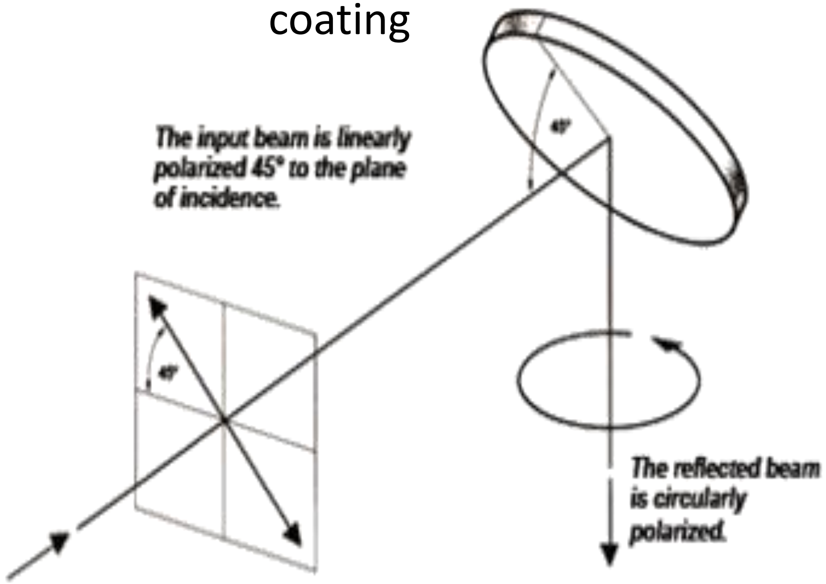
Done
In progress

# Facility Upgrades: Flexible Polarization Rotator



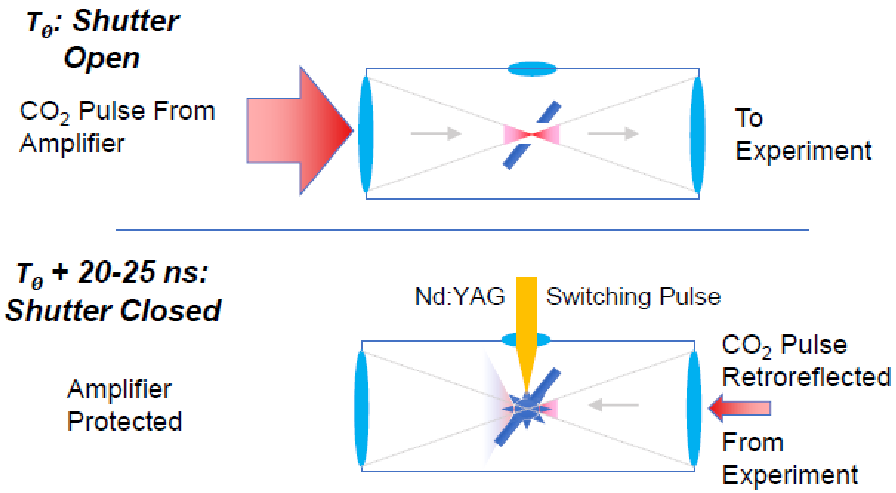


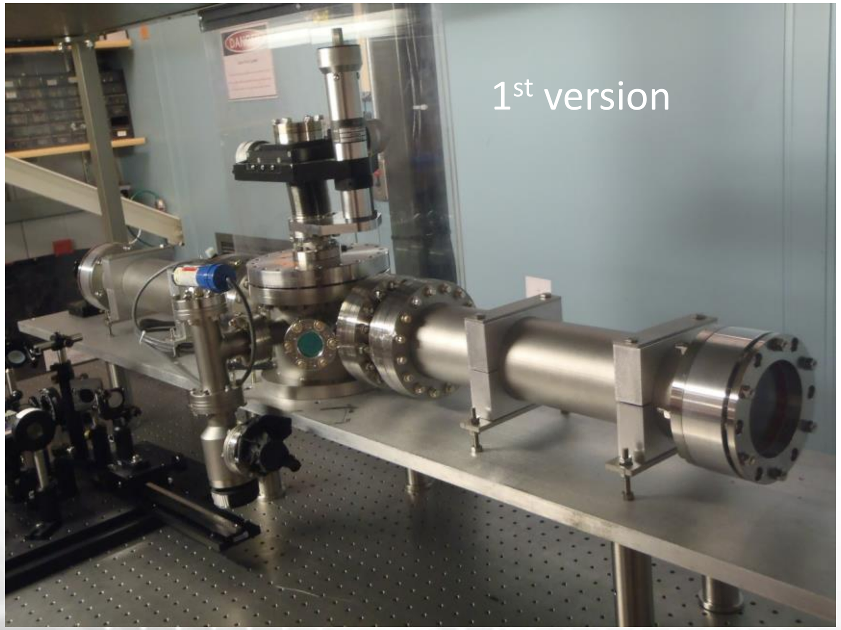
A circular polarizer using a mirror with a quarter-wave coating

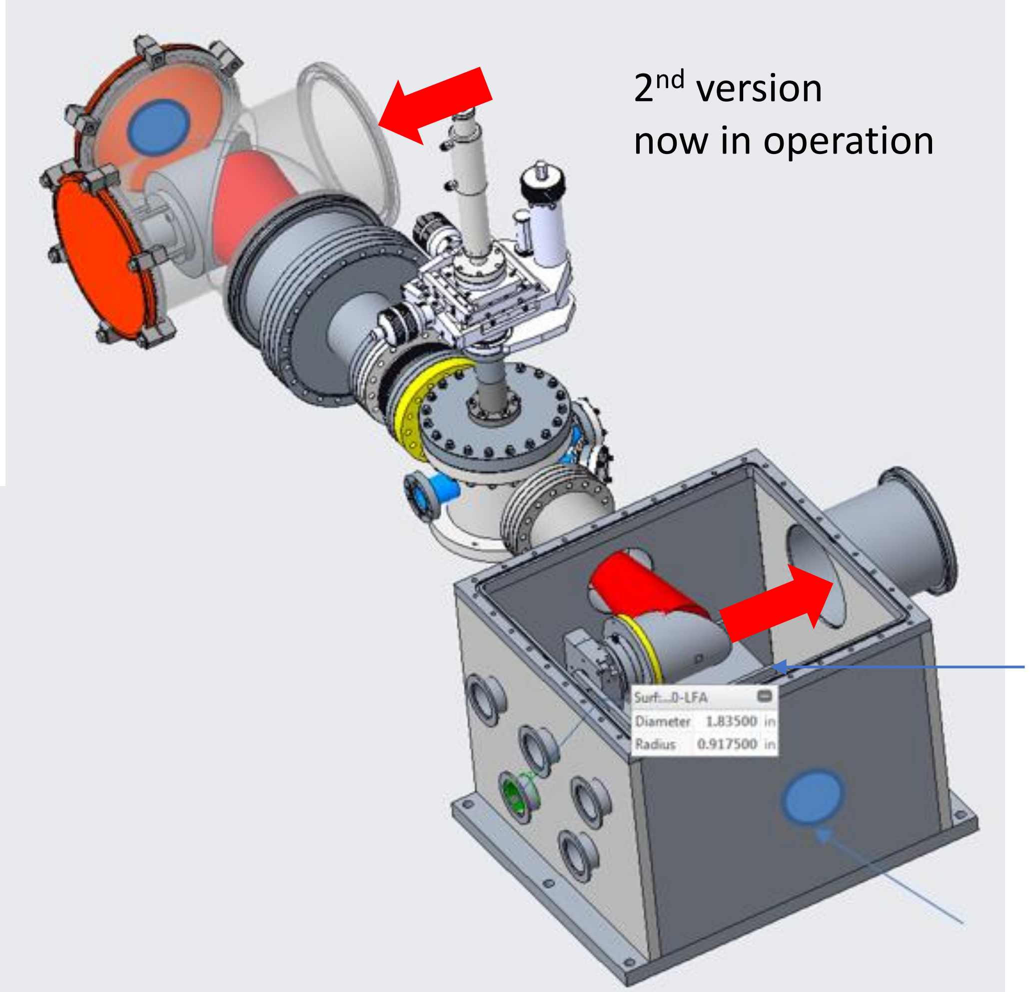


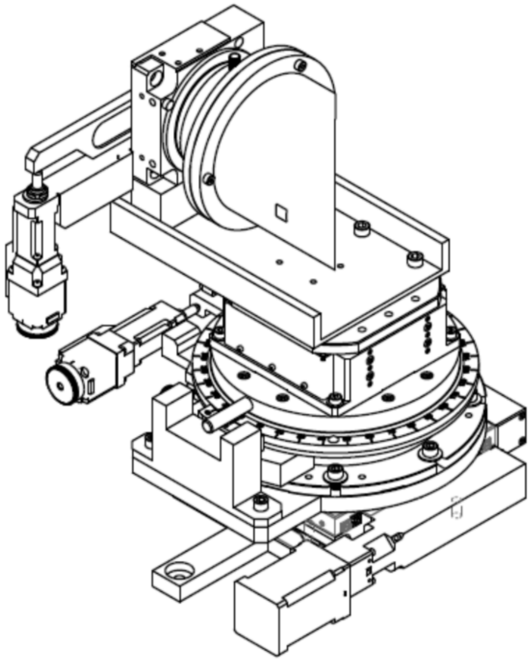

- Rotating plane of incidence by $\alpha^0$ off the initial plane of polarization makes the polarization flip by $2\alpha^0$ after three reflections
- 3 mirrors in a rigid frame rotating by a motorized worm gear around the beam axis will be arranged to preserve the beam pointing stability
- Replacing the $90^0$ turn Cu mirror after the FPR with a mirror having a $\lambda/4$ coating provides circular polarization at the $22.5^o$ FPR turn

# Facility upgrades: Plasma shutter



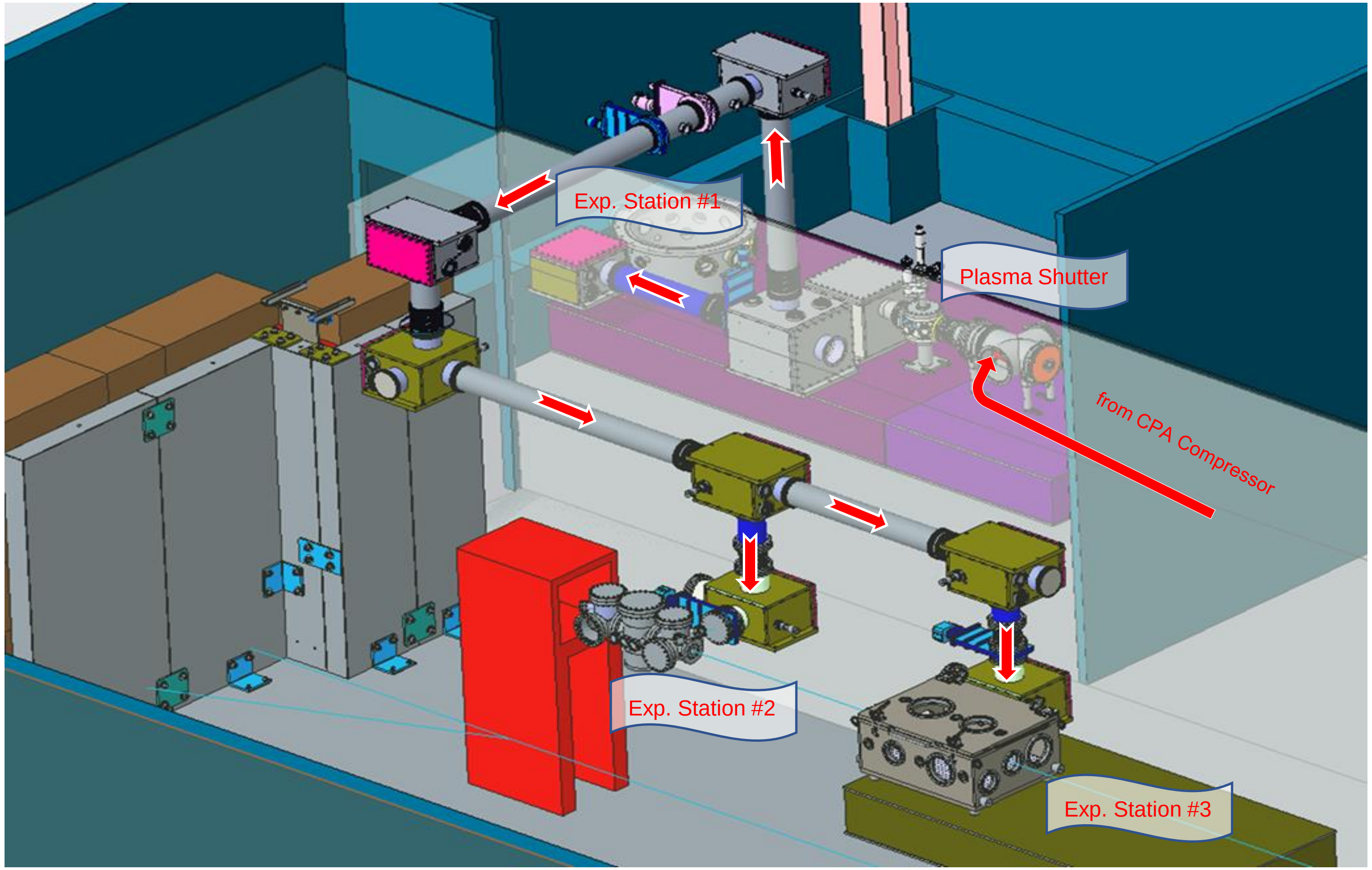



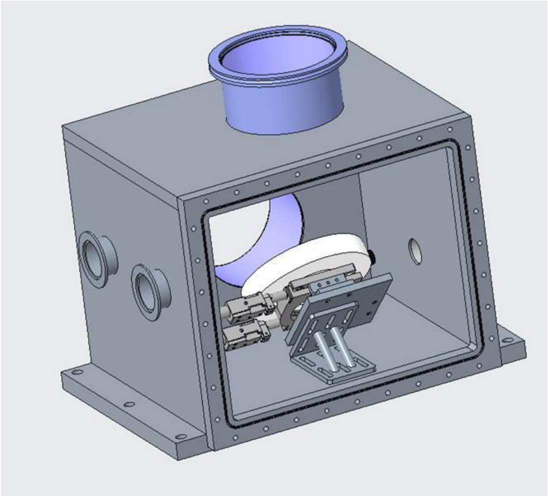



Fully motorized in-vacuum controls

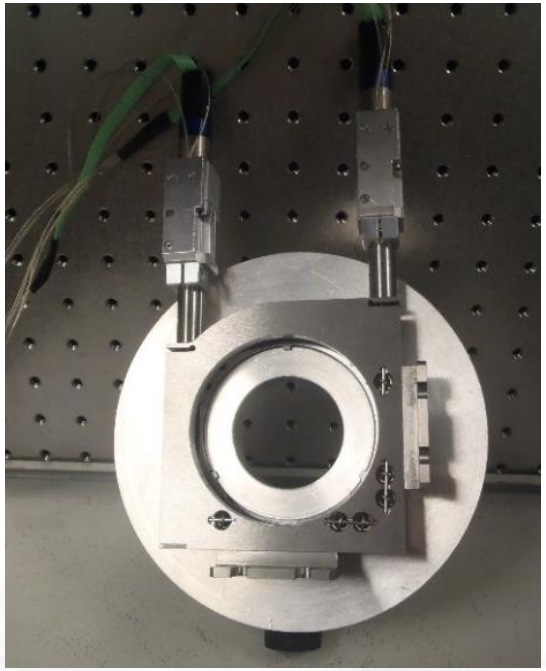
Plasma shutter based on parabolic reflectors eliminates the laser damage from amplified reflection caused by lenses reduces nonlinear beam distortions, and serve as the entry element to the vacuum beam transport

# Facility Upgrades: In-vacuum $CO_2$ laser beam delivery



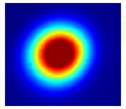
Mirror box



Motorized, in-vacuum mirror mount holds 6” Cu mirror

- Eliminates Kerr effect and beam “dancing” in air
- Protects optics

- Pointing stability 100 $\mu$rad
- Low optical losses
- Minimal beam distortions

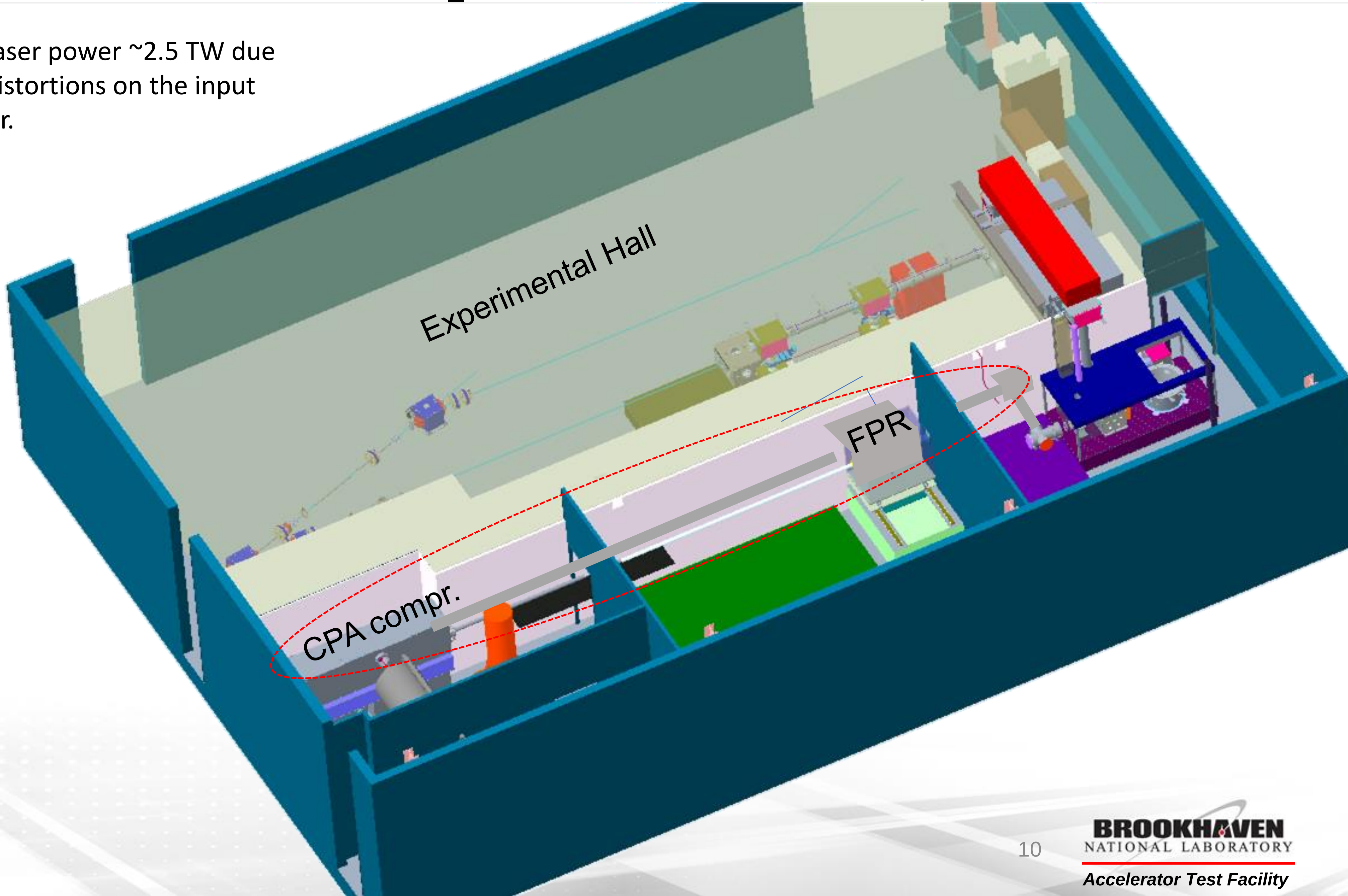


# Facility Upgrades: In-vacuum $CO_2$ laser beam delivery

- Present limit to delivered laser power ~2.5 TW due to the compressed beam distortions on the input window to a plasma shutter.

- To deliver 5 TW, we plan extending vacuum transport all the way to final amplifier to include a CPA Compressor and Polarization Rotator.

- The input window will see only a stretched pulse. This will eliminate the current power limitation.



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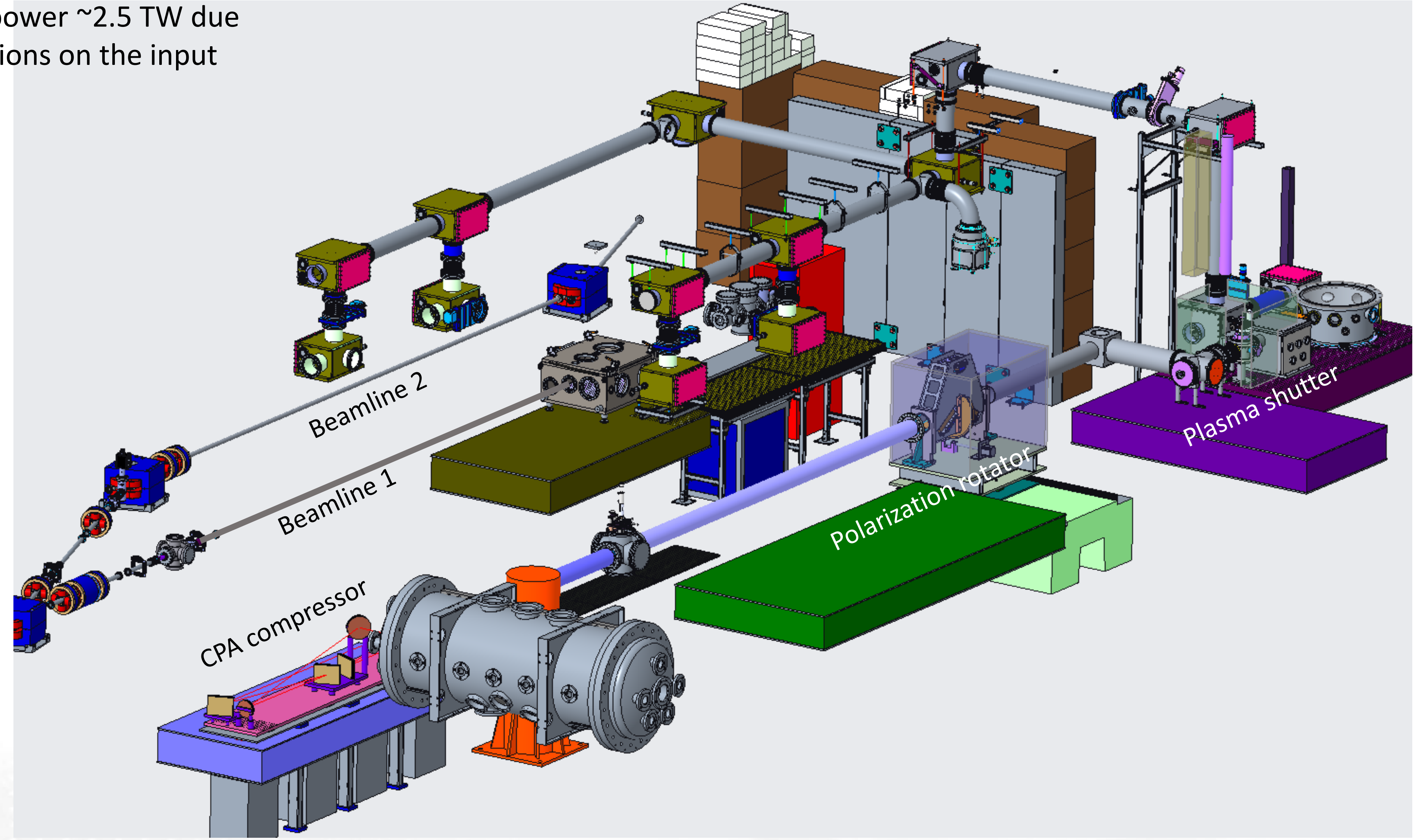
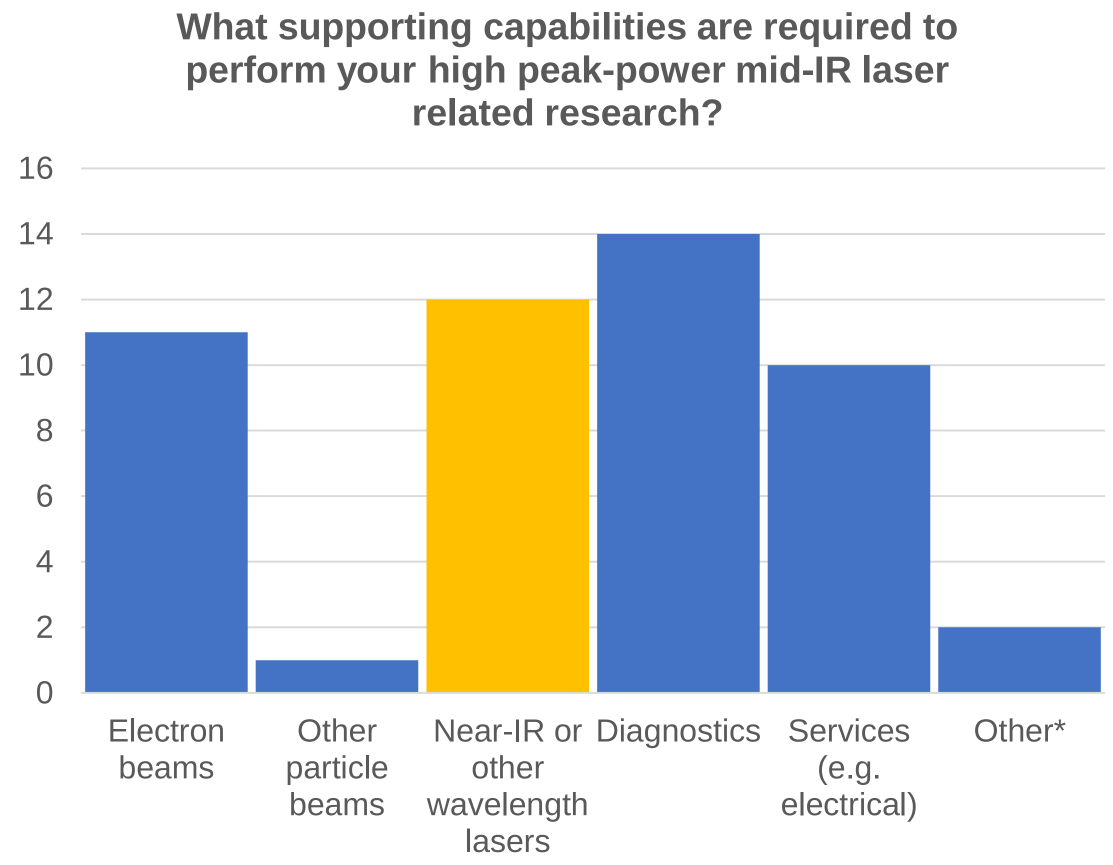


# Response from 2017 community survey

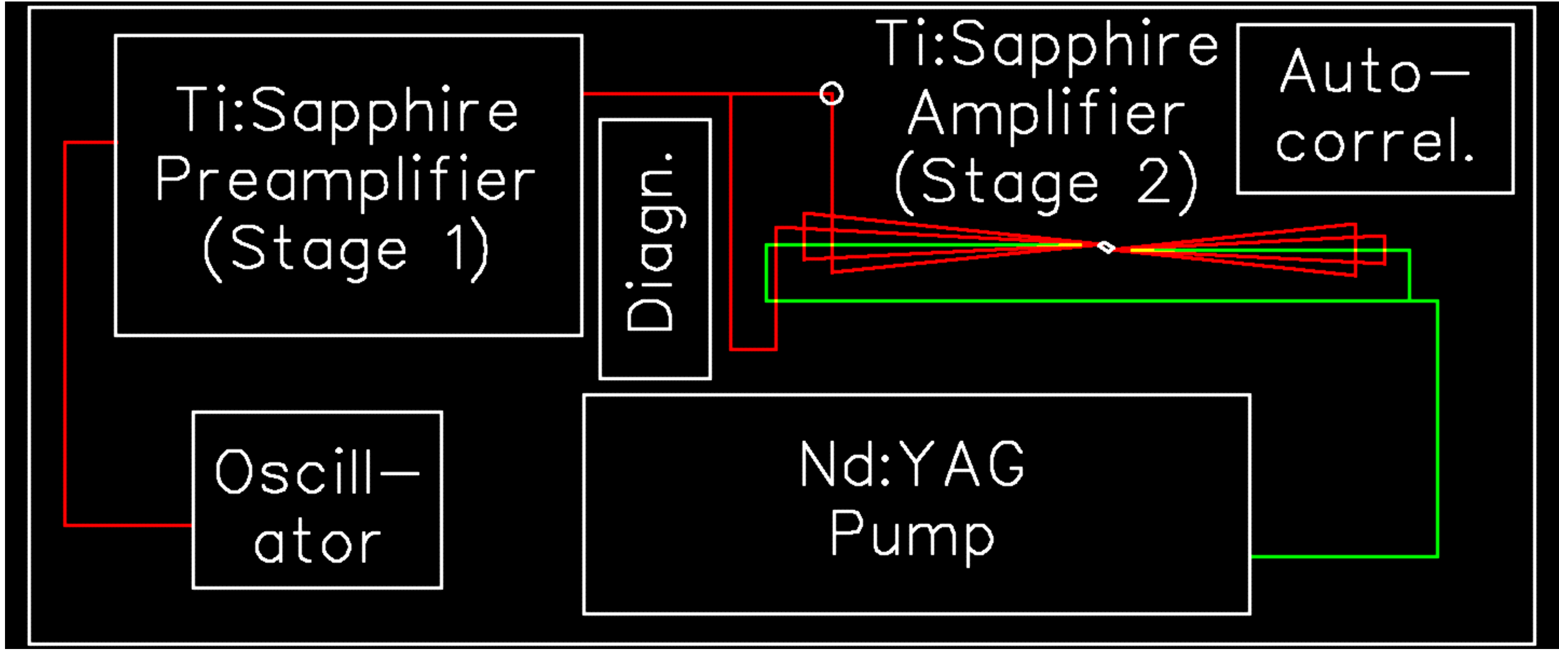



Current uses for a NIR laser:

- Plasma diagnostics
- Ionization injection
- Hard x-ray ICS
- Femtosecond Mid-IR pulses by Kerr effect in plasma

# Ti:Sapphire system

*A new Ti:Sapphire laser system will expand near-IR laser capabilities at ATF enabling high-resolution optical probing and ionization injection for LWFA.*

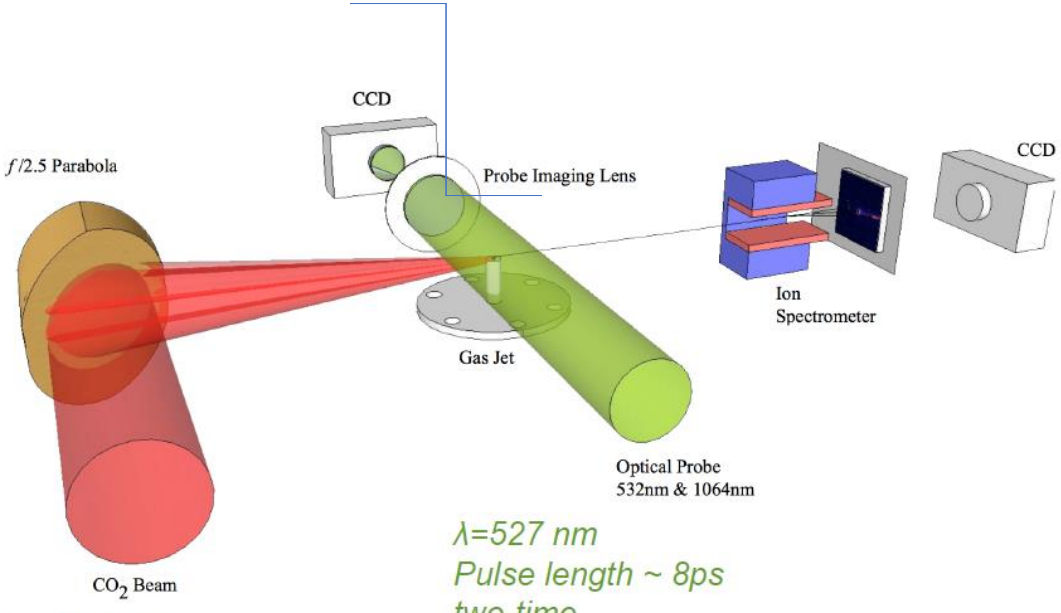



| Parameter | Units | Stage 1 | Stage 2 |
|---|---|---|---|
| Central Wavelength | nm | 800 | |
| FWHM Bandwidth | nm | 20 | 13 |
| Chirped Energy | mJ | 10 | 200 |
| Compressed Energy | mJ | 7 | 100 |
| Maximum Compressed FWHM Pulse Width | fs | 50 | 75 |
| Minimum Energy Deliverable to Experiments | mJ | 5 | 80 |
| Minimum Power Deliverable to Experiments | TW | 0.1 | 1 |

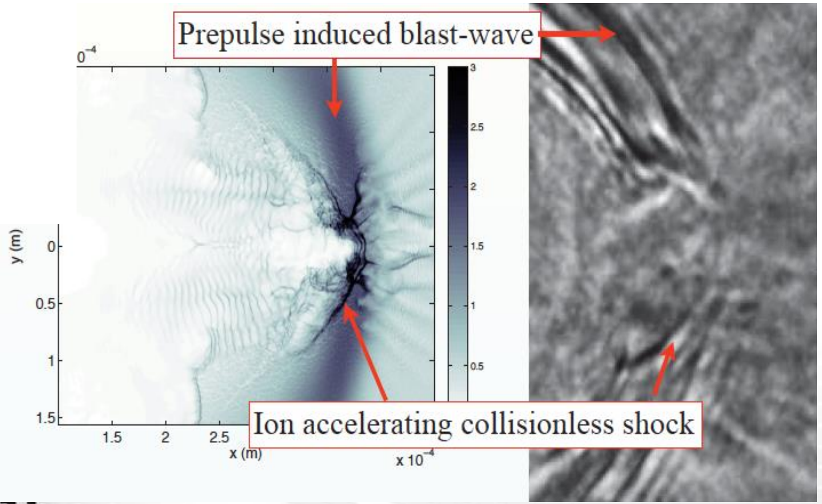
- *Stage I under testing*
  - *Coherent Vitara-T oscillator (loaned from NRL)*
  - *UpTek preamplifier*
- *Stage II planned for next year, pump laser ready for testing*
- *Transport to IP's being modified for delivery next year*

# Applications for a femtosecond near-IR laser

*Mapping plasma density*



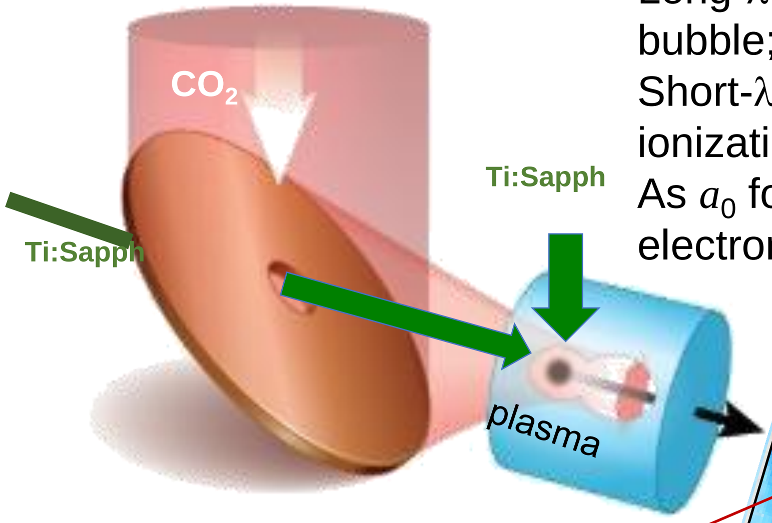

*λ=527 nm*
*Pulse length ~ 8ps*
*two-time*

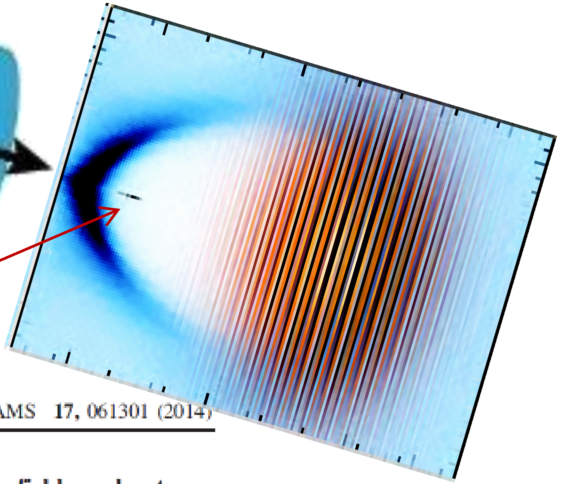



*Ionization injection*

$$a_o = eE / m\omega c$$

Long-λ laser efficiently produces a big bubble;
Short-λ laser provides precision ionization injection.
As $a_0$ for short-λ laser is low, injected electrons are cold and emittance low.



$\varepsilon_n$=20-50 nm

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 061301 (2014)

**Low emittance electron beam generation from a laser wakefield accelerator using two laser pulses with different wavelengths**

X. L. Xu, Y. P. Wu, C. J. Zhang, F. Li, Y. Wan, J. F. Hua, C.-H. Pai, and W. Lu*
*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
P. Yu, C. Joshi, and W. B. Mori

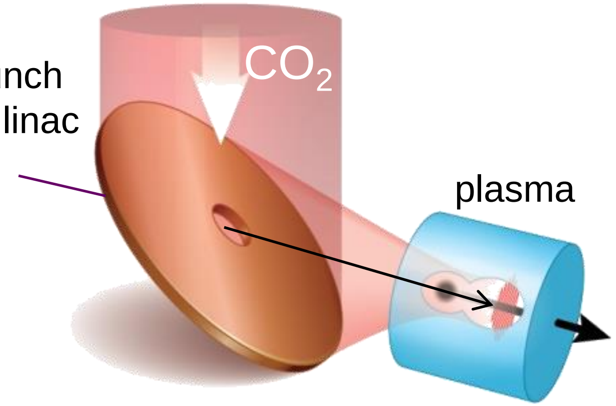
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 17, 101301 (2014)

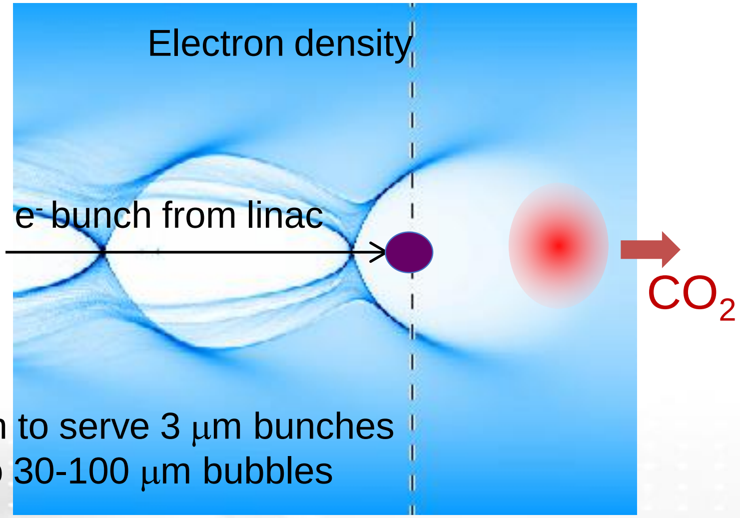
**Thermal emittance from ionization-induced trapping in plasma accelerators**

C. B. Schroeder,[1] J.-L. Vay,[1] E. Esarey,[1] S. S. Bulanov,[2,1] C. Benedetti,[1] L.-L. Yu,[3] M. Chen,[3] C. G. R. Geddes,[1] and W. P. Leemans[1,2]

# LWFA combined with RF linac

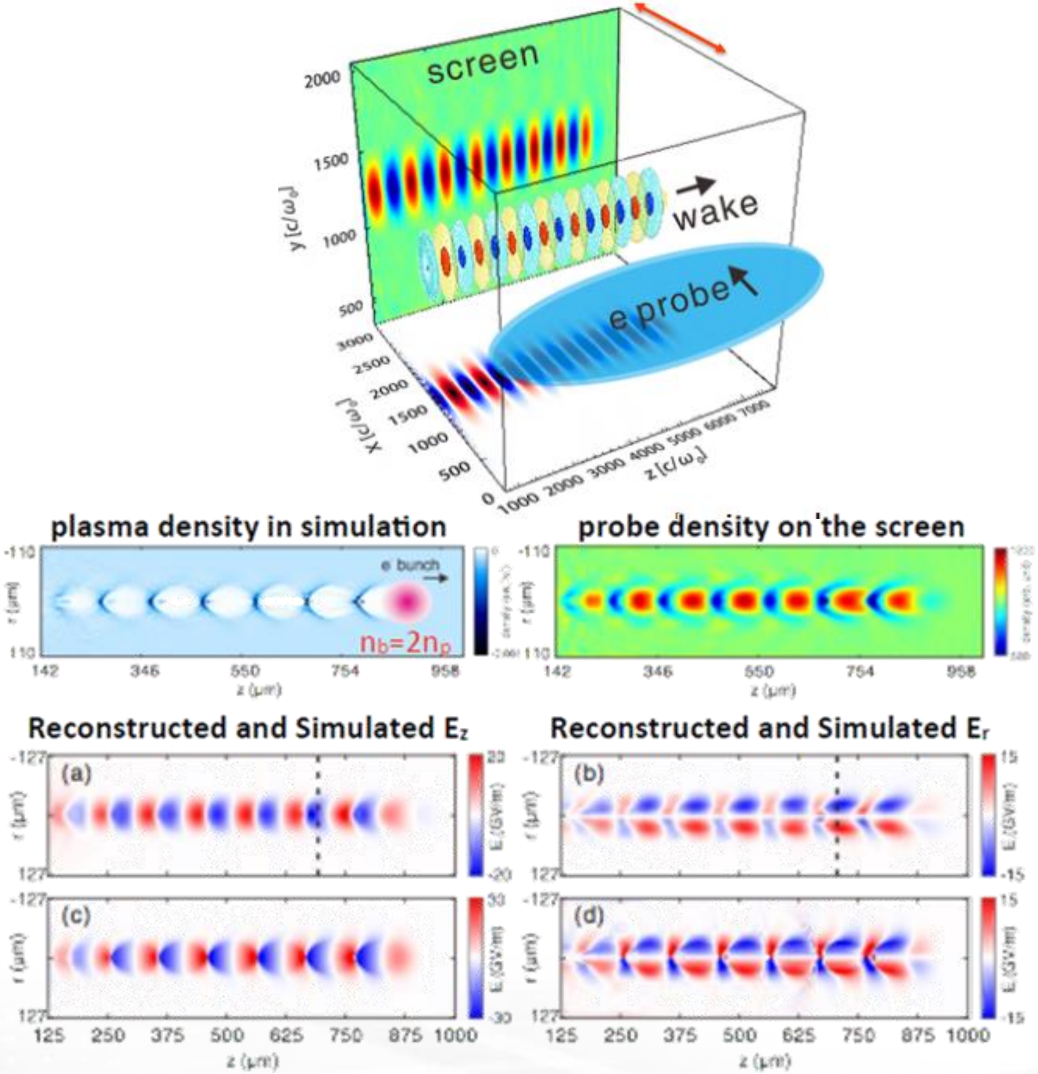
Unique opportunity for injecting a controlled femtosecond bunch into a plasma bubble for probing, seeding, staging



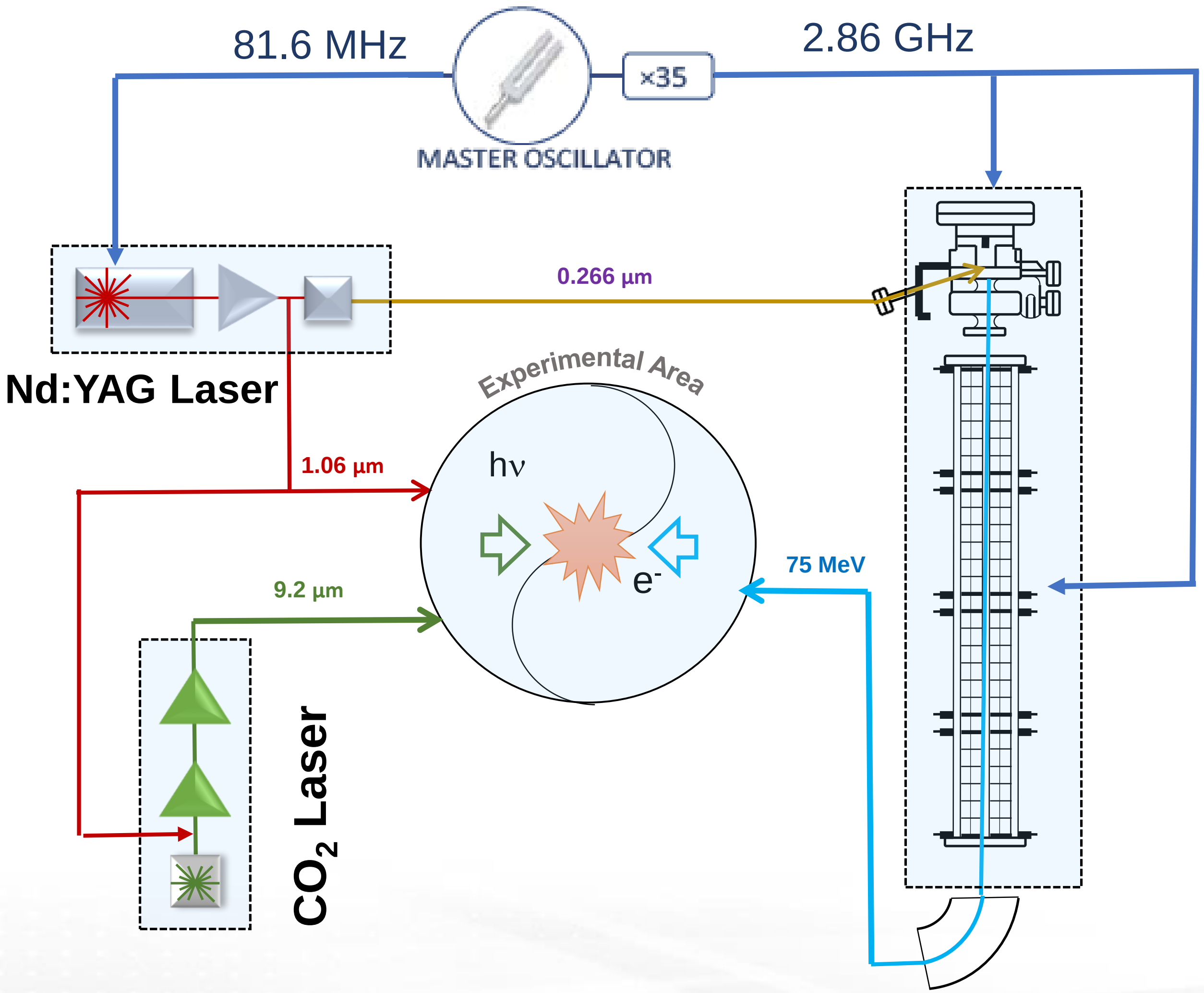




Plan to serve 3 μm bunches into 30-100 μm bubbles

Capturing wake field structures



# Linac/laser Synchronization

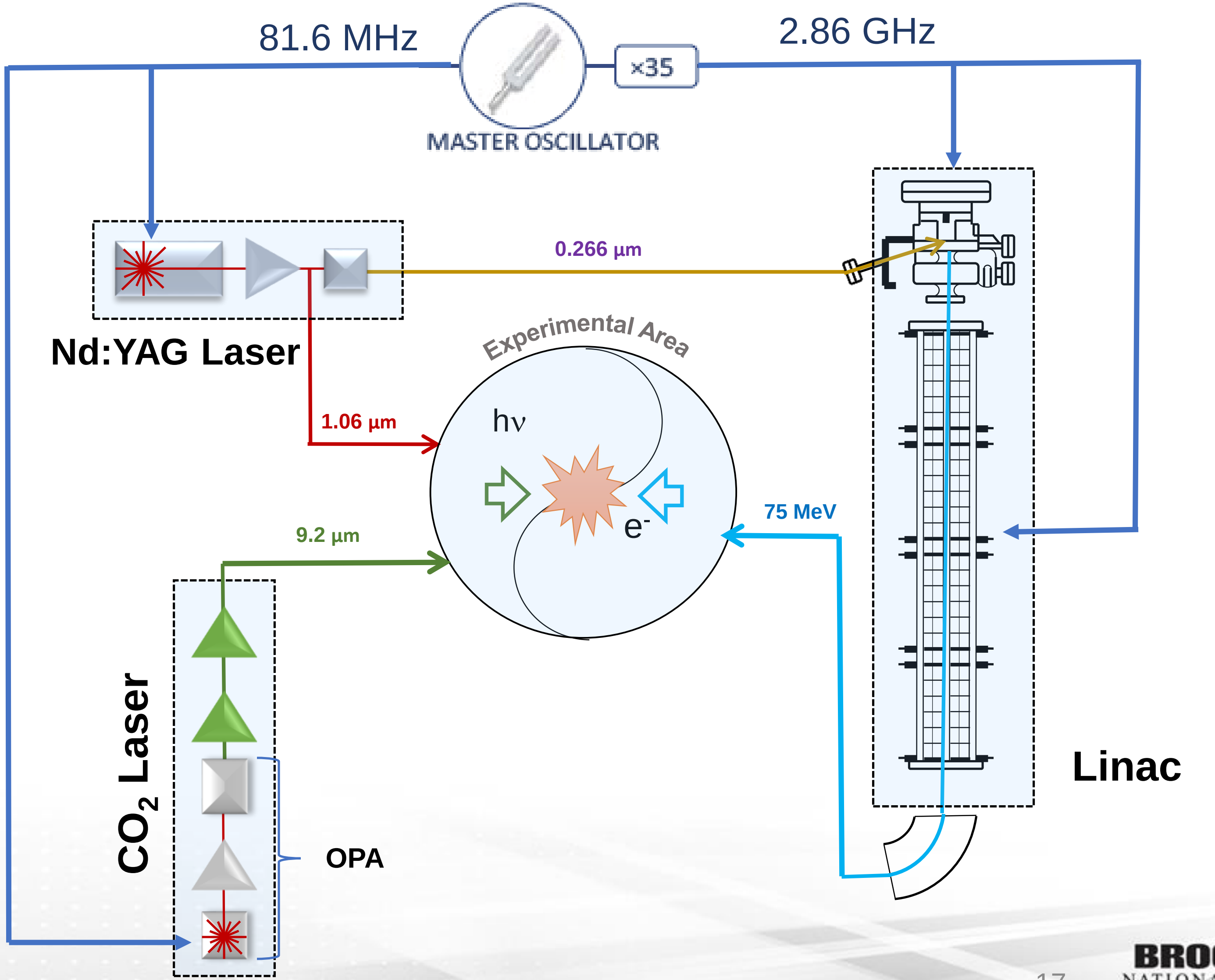



- **Previous System:** based on optical slicing of a picosecond LWIR pulse from a CO2 laser oscillator using a Ge switch controlled with YAG laser

# Linac/laser Synchronization

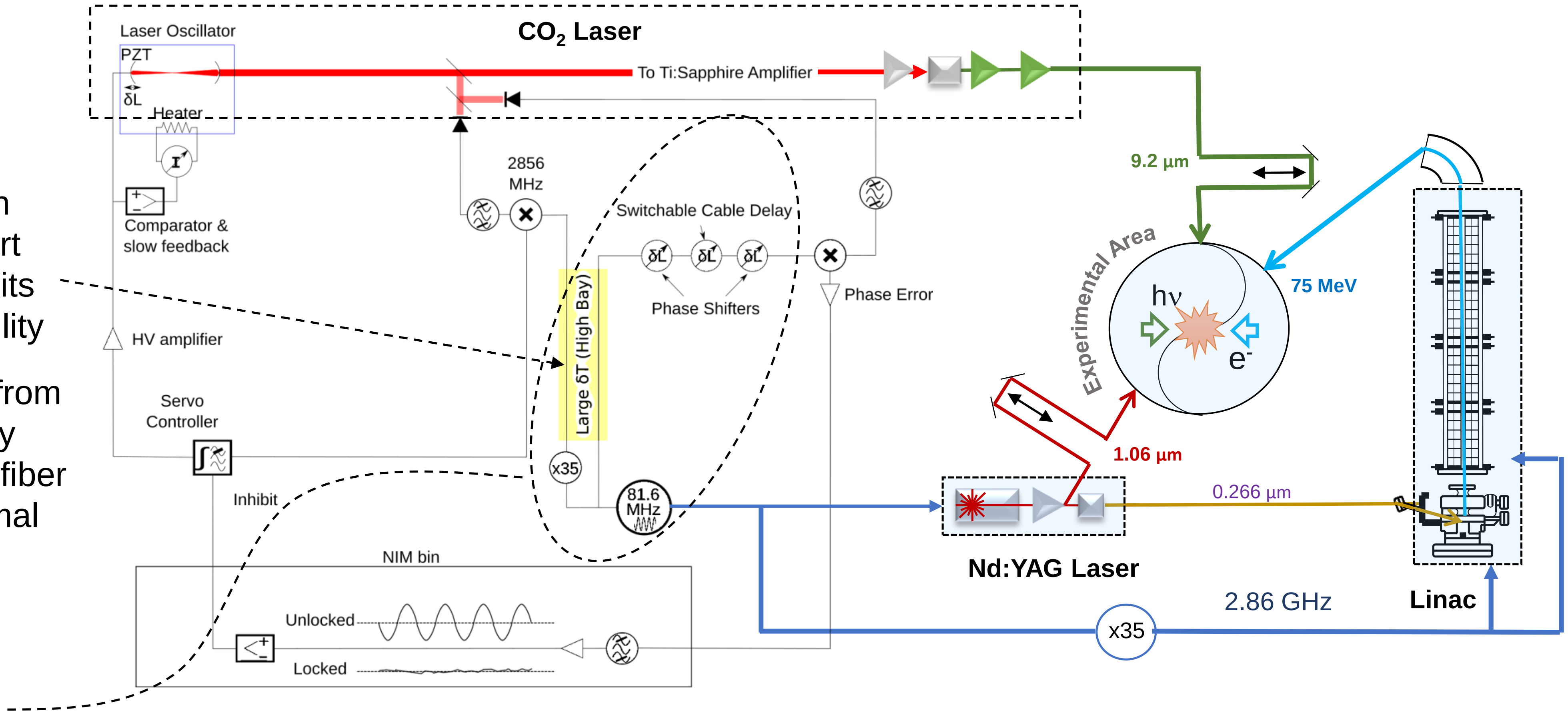
- **Current System:**
  Utilizes electronic phasing of a femtosecond OPA, which is used as the front end for the $CO_2$ laser system

- Accuracy ≤250 fs based on experimental data



# Linac/laser Synchronization

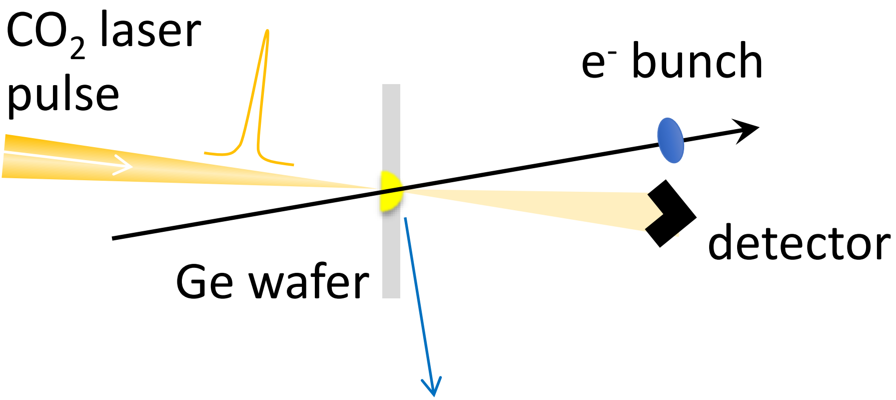
- Electronic phasing scheme relies of frequency mixing
- Thermal phase drift in coaxial cable transport around the facility limits our phase locking ability
- Next steps: Migrate from coax-based frequency distribution to optical fiber with ~10x lower thermal phase drift.




- Replace RF components with fiber-coupled, free-space, multi-pass optical trombone to provide:
  - No loss of phase-locking during motorized adjustment and utilizing existing control system
  - ”Point and Click” delay adjustments by users

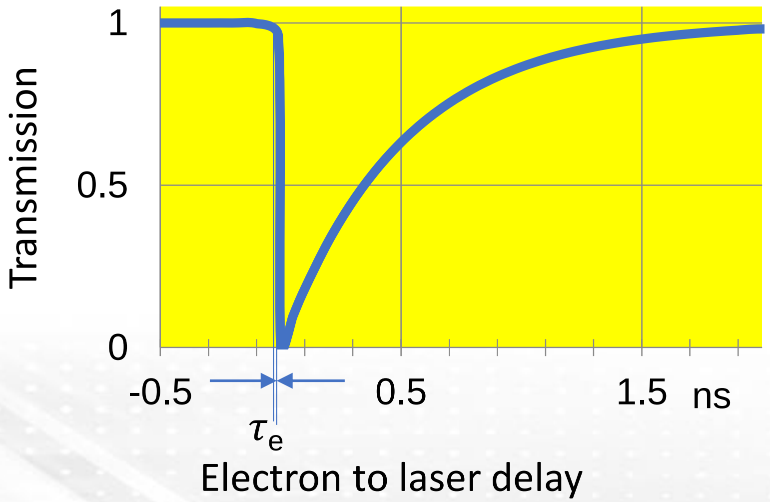
# Establishing laser/e-bunch temporal and spatial overlap

### Induced absorption in semiconductor




- Precision down to laser/e$^-$ beam pulse width

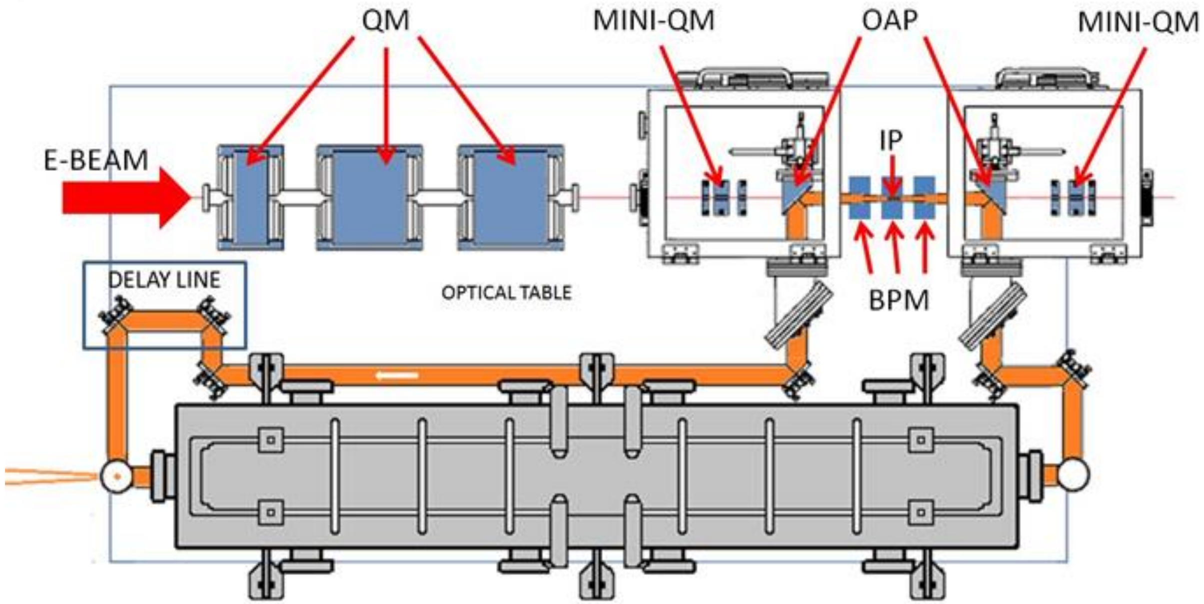
### Transient Behavior




### Streak camera

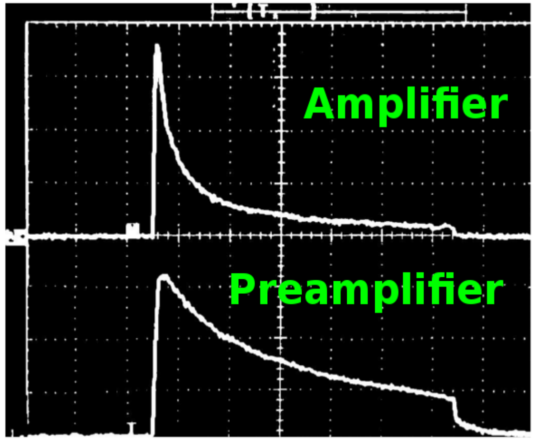
- Combine laser and transition radiation on a streak camera
- ~2 ps resolution

# Multi-pulse regime for laser/e-beam interactions

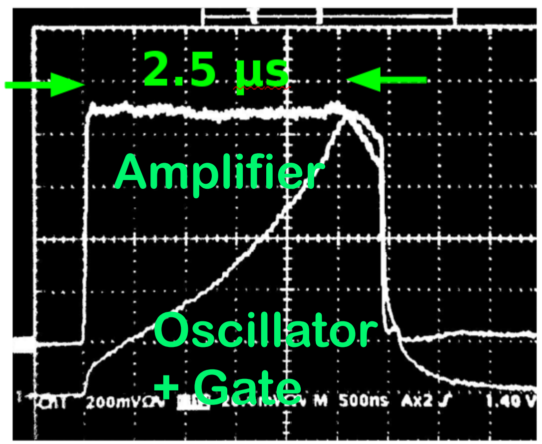



YAG laser pulse trains

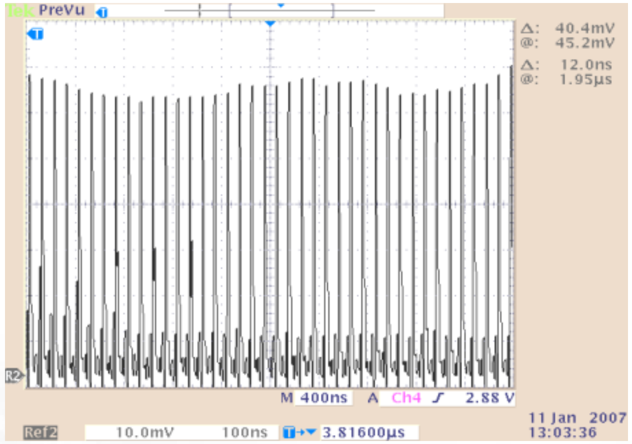
Before compensation




After compensation




Synchronized $CO_2$ pulse train in a recirculation cavity




- Based on $CO_2$ laser pulse circulation in a regenerative cavity and matching electron bunch trains.
- Arbitrary waveform generator compensates gain depletion throughout YAG pulse train producing up to 200 pulses flat within 5%.
- Bunch trains used extensively in FEL oscillator experiment ca. 1997, and since 2011 for ICS and IFEL recirculation cavity experiments.
- Experiment reveals ≤250 fs synchronization accuracy

# ATF Planning is Closely Aligned with the Scientific Needs Identified in the SNW2017 Report

- **Improved Performance for Users**
  - Delivery of 5 TW @ 2 ps to user IPs ⇨ All-vacuum beam delivery (include CPA compressor and FPR)
  - Plasma shutter
  - Flexible polarization control
  - Upgraded synchronization and timing capabilities
  - Expanded diagnostics
- **Further increases to delivered power @ 2 ps by means of:**
  - Apodizing optics
  - Improved amplifier with expanded discharge cross-section and 6” output window
  - New CPA master gratings with significantly higher damage threshold
- **R&D on pulse compression targeting >10 TW @ 1-0.5 ps:**
  - NLPC – *ongoing with 1 TW @ 1 ps and 600 fs at lower power demonstrated, 3-year Stewardship sponsored program initiated*
  - Investigate broadband mixtures and a strongly saturated regime
- **E-beam improvements**
  - Femtosecond bunch compressor
  - 2nd x-band deflecting cavity
  - Higher energy

# Thank you!