5 TW

Multi-TW

2 ps

Picosecond

9.2 μm

Long-Wave Infrared

Laser for Particle Acceleration at ATF

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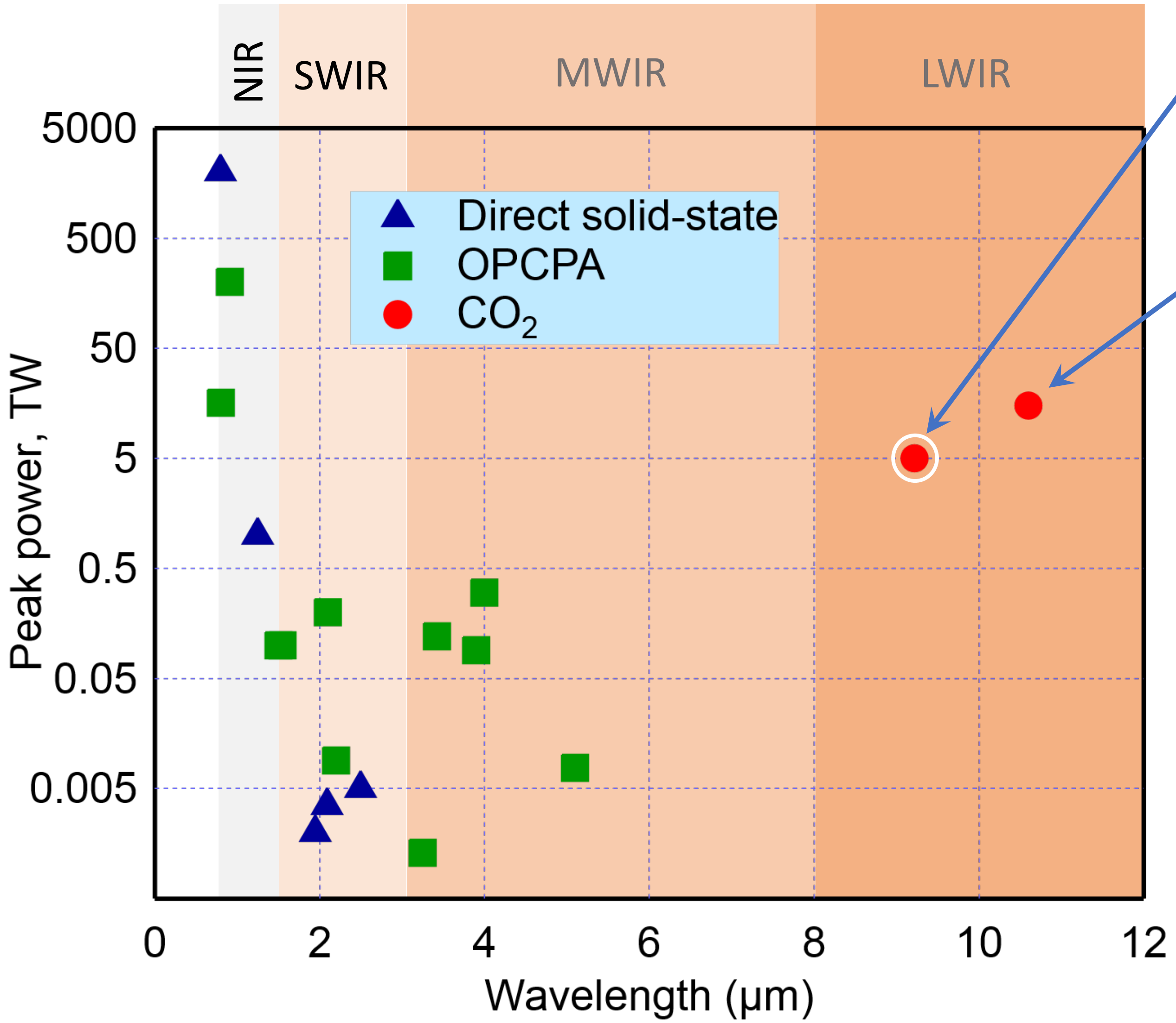
--- *Brookhaven National Laboratory, Accelerator Test Facility* ---

High peak-power IR lasers



ATF 2019

Single 2-ps pulse, 5 TW

UCLA 2010

Train of 3-ps pulses, 15 TW

Compilation: Sara Bucht (LLE)

Direct solid state

Y. Chu et al., Opt. Express 21, 29231 (2013)

M. B. Agranat et al., Quantum Electron. 34, 506 (2004)

C. Gaida et al., Opt. Lett. 41, 4130-4133 (2016).

E. Slobodchikov et al., Proc. SPIE 9726, 972603 (2016)

P. Malevich et al., Opt. Lett. 41, 930 (2016).

OPCPA

V. V. Lozhkarev et al., Proc. SPIE 6100, 61001D (2006)

D. Herrmann et al., Opt. Lett. 34, 2459 (2009)

O. D. Mücke et al., Opt. Lett. 34, 2498 (2009

J. V. Rudd et al., Opt. Lett. 30, 1974 (2005)

Y. Deng et al., Opt. Lett. 37, 4973 (2012)

U. Elu et al., Optica 4, 1024 (2017)

J. Moses et al., Opt. Lett. 34, 1639 (2009)

K. Zhao et al., Opt. Lett. 38, 2159 (2013)

A. V. Mitrofanov et al., Optica 3, 299 (2016).

G. Andriukaitis et al., Opt. Lett. 36, 2755 (2011)

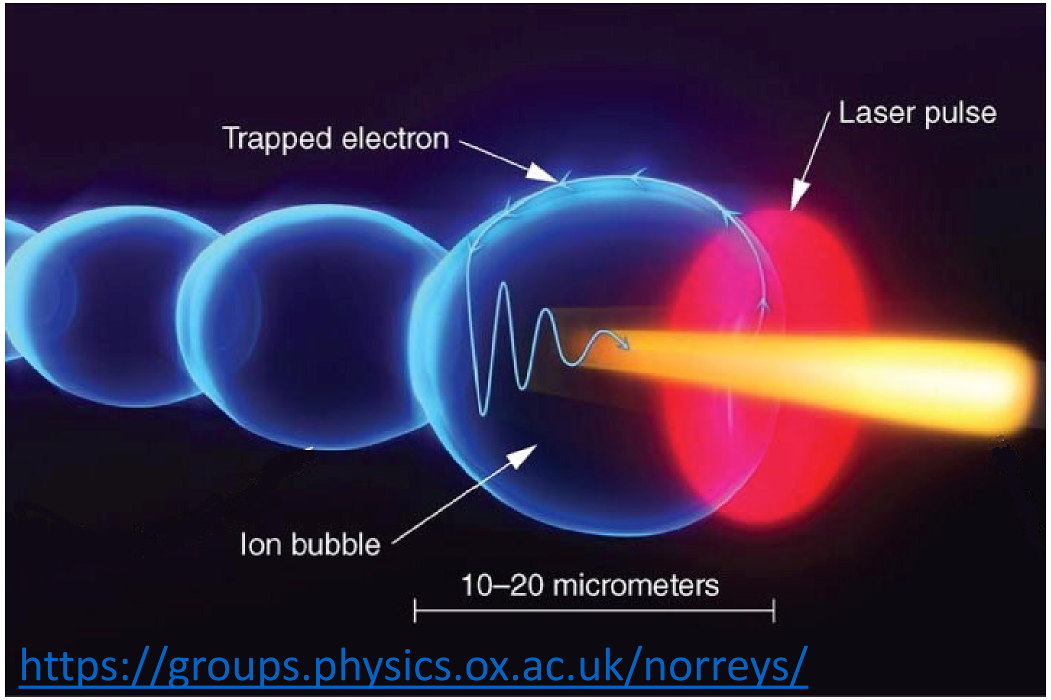
L. von Grafenstein et al., Opt. Lett. 42, 3796 (2017)

CO_2

D. Haberberger et al., Opt Express 18, 17865 (2010)

M. Polyanskiy et al., to be published

Laser Wakefield Acceleration



Bubble size

Near-IR	(λ ~1 μm)	**10s of μm**
LWIR	(λ ~10 μm)	**100s of μm**

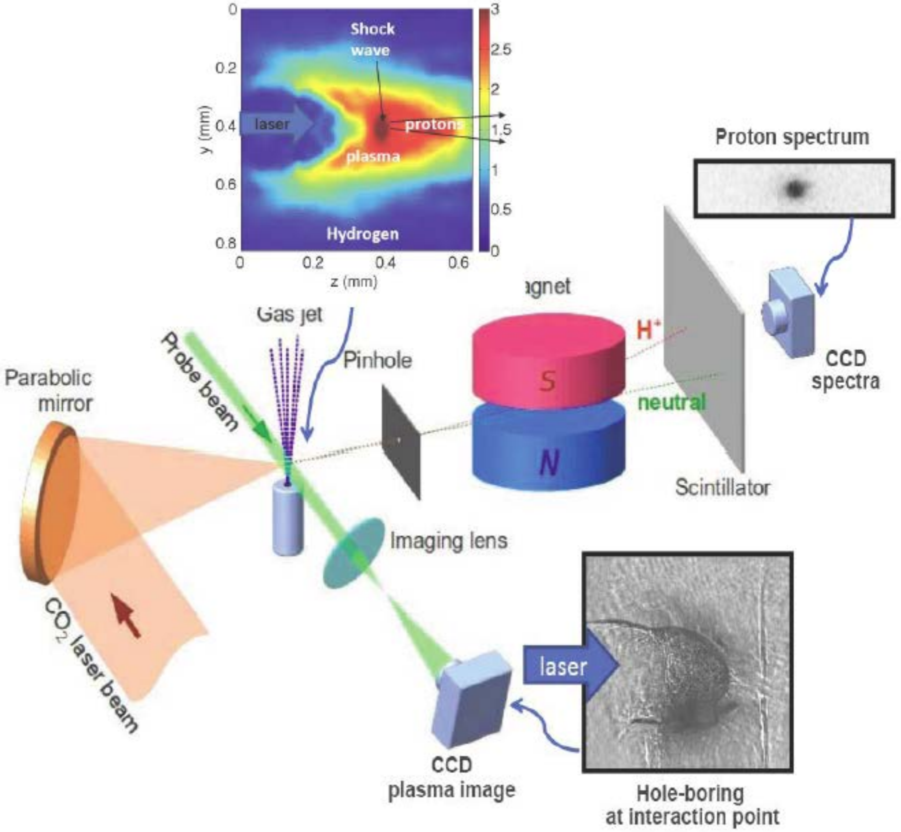
1000x volume!

Laser Acceleration of Ions

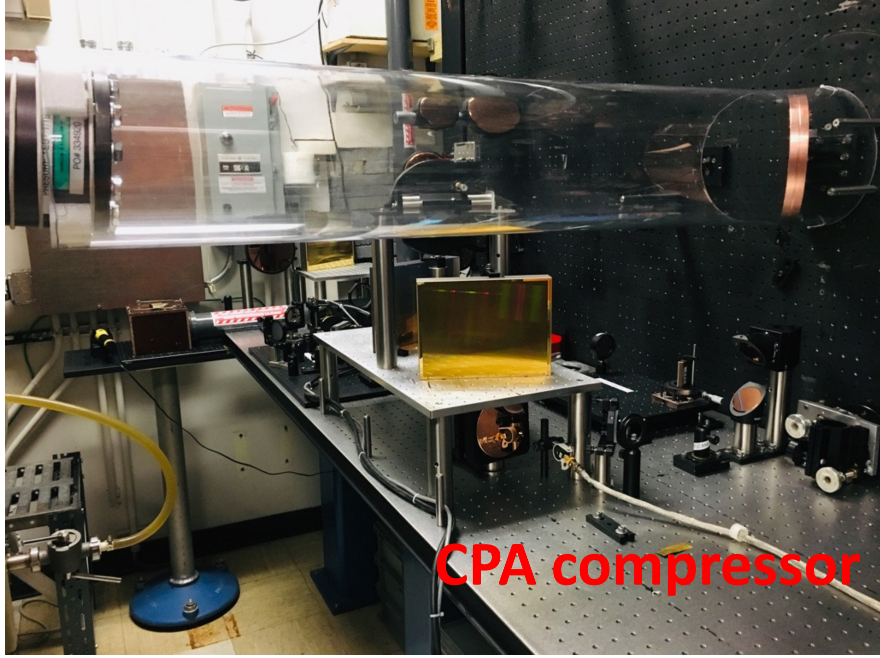
Critical plasma density

Near-IR	(λ ~1 μm)	**~10^{21} cm^{-3}**
LWIR	(λ ~10 μm)	**~10^{19} cm^{-3}**

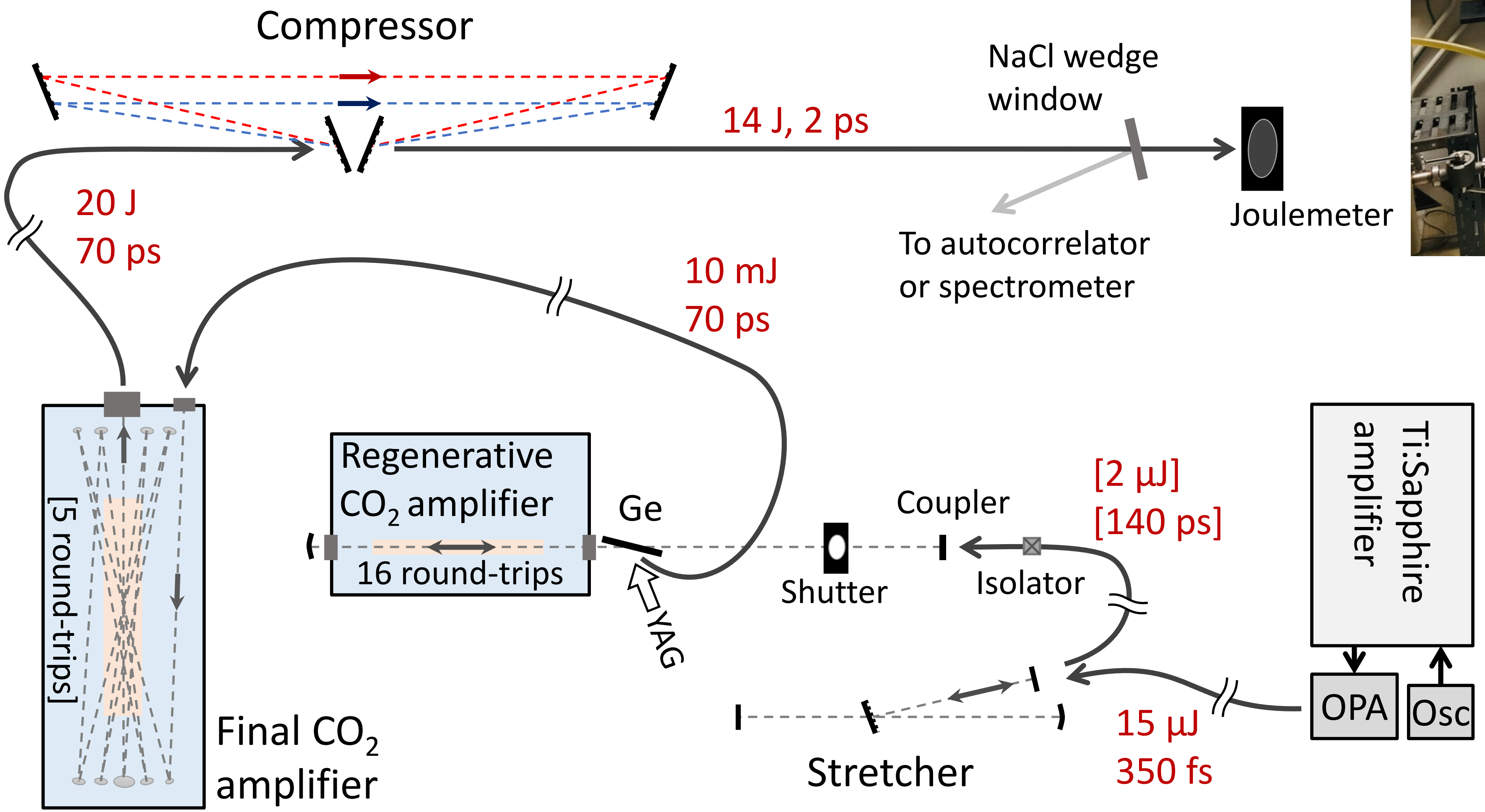
Foil → Gas jet



ATF's **5 TW Long-Wave IR** (9.2 μm) Laser



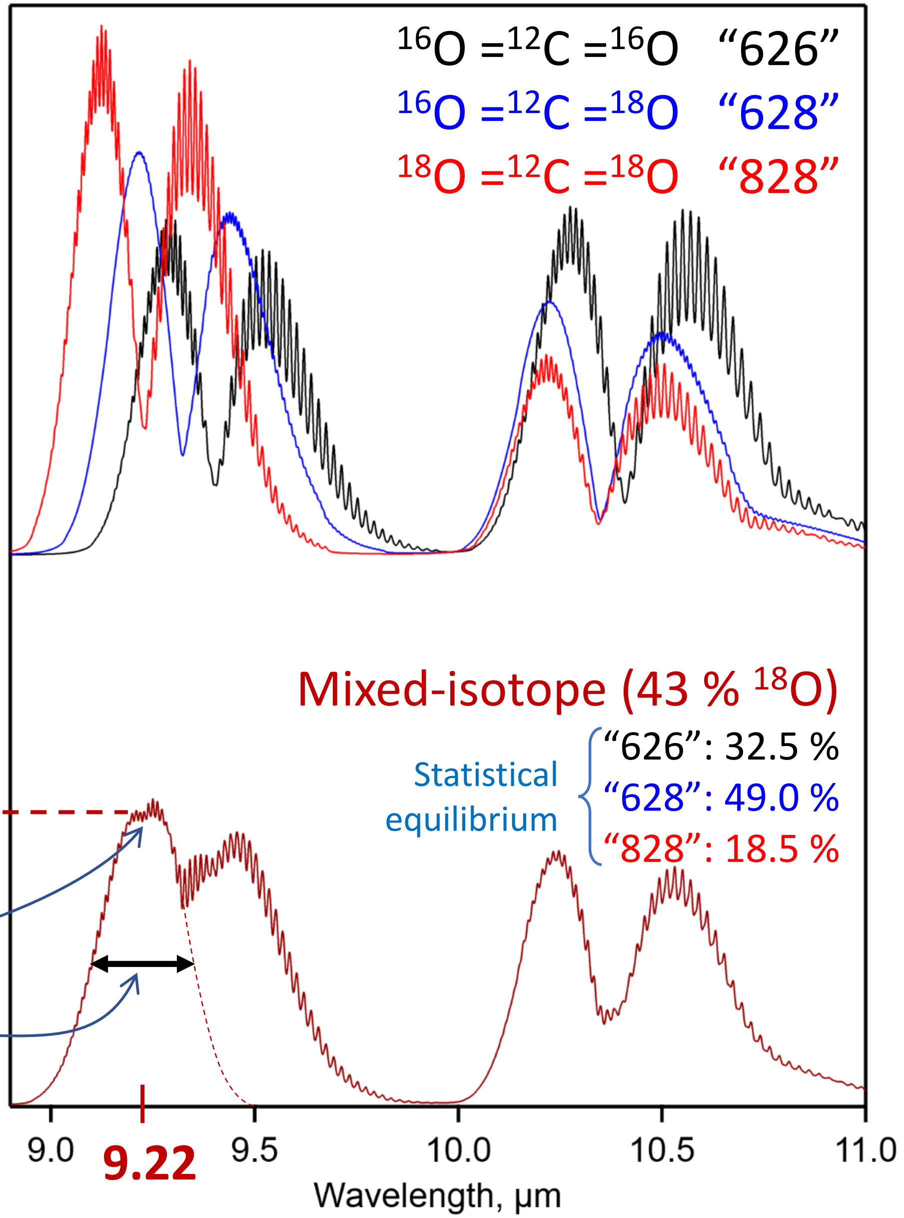
Footprint: ~3.5×9 m



Key features of ATF's CO_2 laser

- **Solid-state seed laser**
- **Chirped-pulse amplification**
  First gas laser with CPA
- **Isotopic active medium**
  First mixed-isotope picosecond CO_2 laser

Mixed-isotope, high-pressure CO_2 amplifiers



Gain:
1 %/cm (regen)
2 %/cm (final)

~Flattop
~1 THz bandwidth

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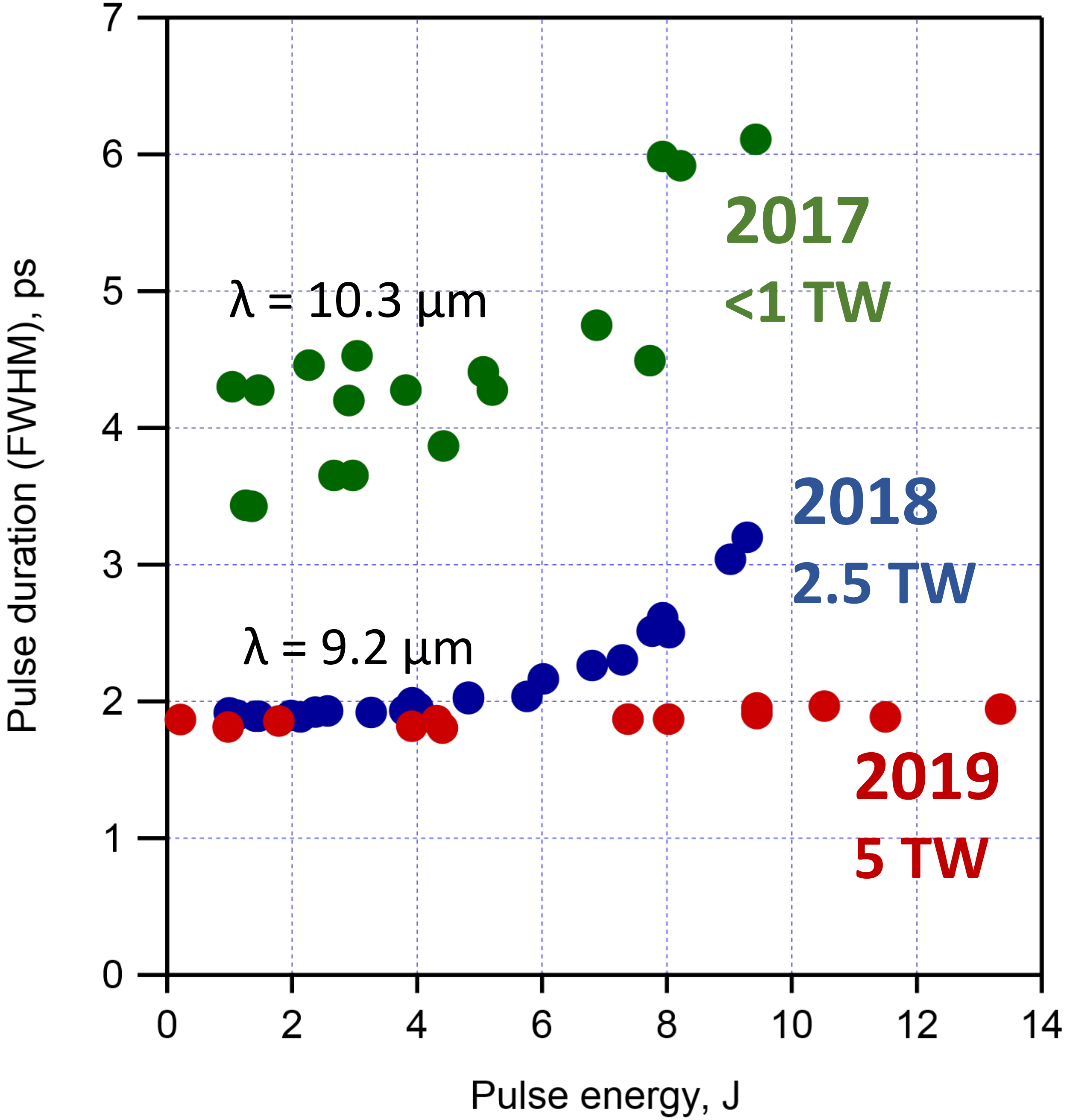
good for amplification of a **2 ps** pulse

Regen (1st amplifier)
10 bar
CO_2: 0.3
N_2: 0.1
He: 9.6
^{18}O: 43 %

Final (2nd amplifier)
8.25 bar
CO_2: 0.5
N_2: 0.25
He: 7.5
^{18}O: 47 %

Recent CPA CO_2 laser development



2017

- mixed-isotope regen
- 66 % of energy in 1st pulse
- compressor efficiency 50 %

2018

- mixed-isotope regen <u>and</u> final amplifier
- 87 % of energy in 1st pulse

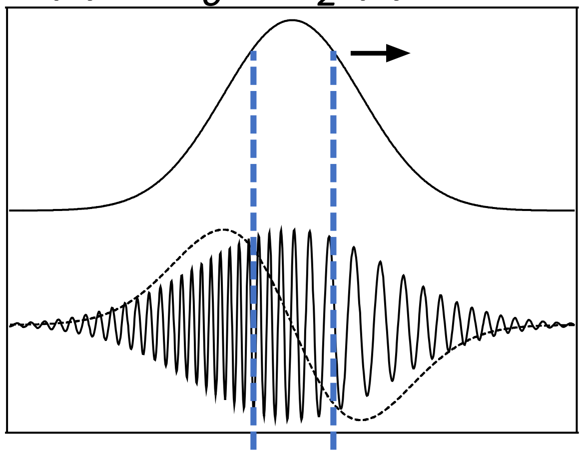
2019

- 2× chirp (denser gratings)
- compressor efficiency 70 %

2 ps → ~500 fs via nonlinear pulse compression

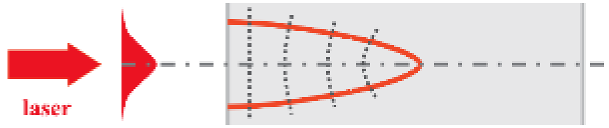
Self-phase modulation

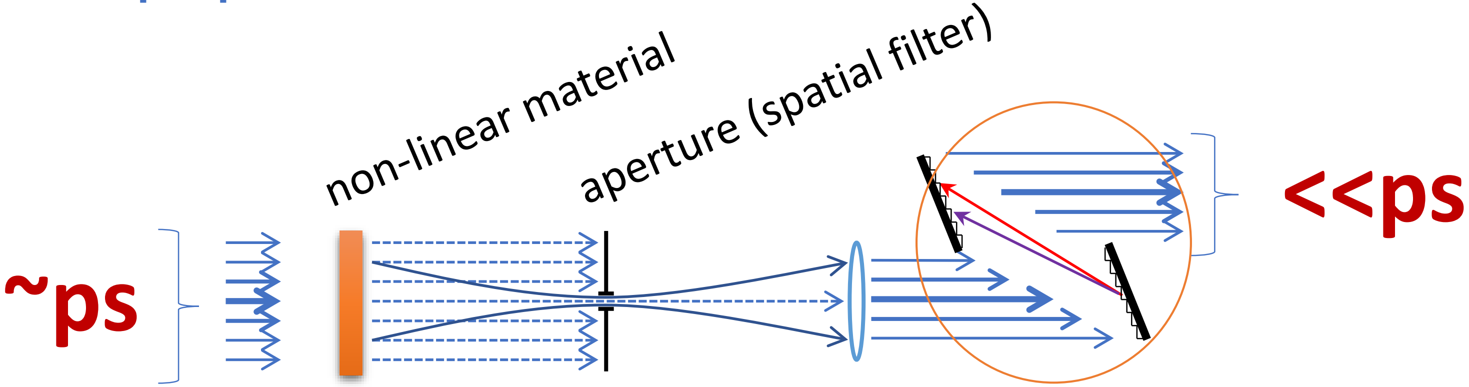
$n(t) = n_0 + n_2 I(t)$



Self-focusing

$n(r) = n_0 + n_2 I(r)$





- **Problem**: very little is known about nonlinear properties of materials in LWIR
- **Solution**: starting a dedicated 3-years R&D program sponsored via a DOE's "Accelerator Stewardship" grant (collaboration with UCF and II-VI Inc)

TW LWIR vs. PW Near-IR

Brut-force unit!

$$Watt = \frac{Joule}{second}$$

Is 5 TW LWIR

200 less than

1 PW Near-IR ?

TW LWIR vs. PW Near-IR

Au, 5 g
USD 246.15

Fe, 1 kg
USD 1.31

TW LWIR vs. PW Near-IR

Brut-force unit!

$$Watt = \frac{Joule}{second}$$

- Good metric for laser cutting

- May not be good for other applications

TW LWIR vs. PW Near-IR

Brut-force unit!

$$Watt = \frac{Joule}{second}$$

Number of photons (Joule)

Optical period (second)

	1 PW @ 1 µm	5 TW @ 10 µm
hν	0.2 aJ (1.2 eV)	0.02 aJ (0.12 eV)
T	3.3 fs	33 fs
photons/T	**1.6e19**	**8e18**

Summary and Conclusions

1) **5 TW at 9.2 μm in a 2 ps pulse**
   - Highest peak power in an isolated LWIR pulse
     (15 TW was demonstrated in 2011 at UCLA in a pulse train)
   - Shortest Terawatt LWIR pulse

2) **Unique features of Brookhaven ATF's LWIR laser**
   - Solid-state seed laser
   - Chirped-pulse amplification (in a gas laser!)
   - Mixed-isotope high-pressure CO_2 power amplifiers

3) **Goals**
   - Deliver high-quality 5 TW beam to in-vacuum experiment locations
     (implement vacuum compressor chamber and vacuum beam transport)
   - Achieve 10+ TW (~500 fs) via nonlinear pulse compression