Long-Wave IR Terawatt Laser Pulse Compression to Sub-Picoseconds

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Outline

- Motivation
- State of art in picosecond CO_2 laser technology
- Path to femtoseconds via nonlinear post-compression
- Simulations
- Experimental results
- Plan for continuation and conclusions

Motivation for multi-TW ultra-fast LWIR

How Laser Wake Field Acceleration benefits from higher λ?

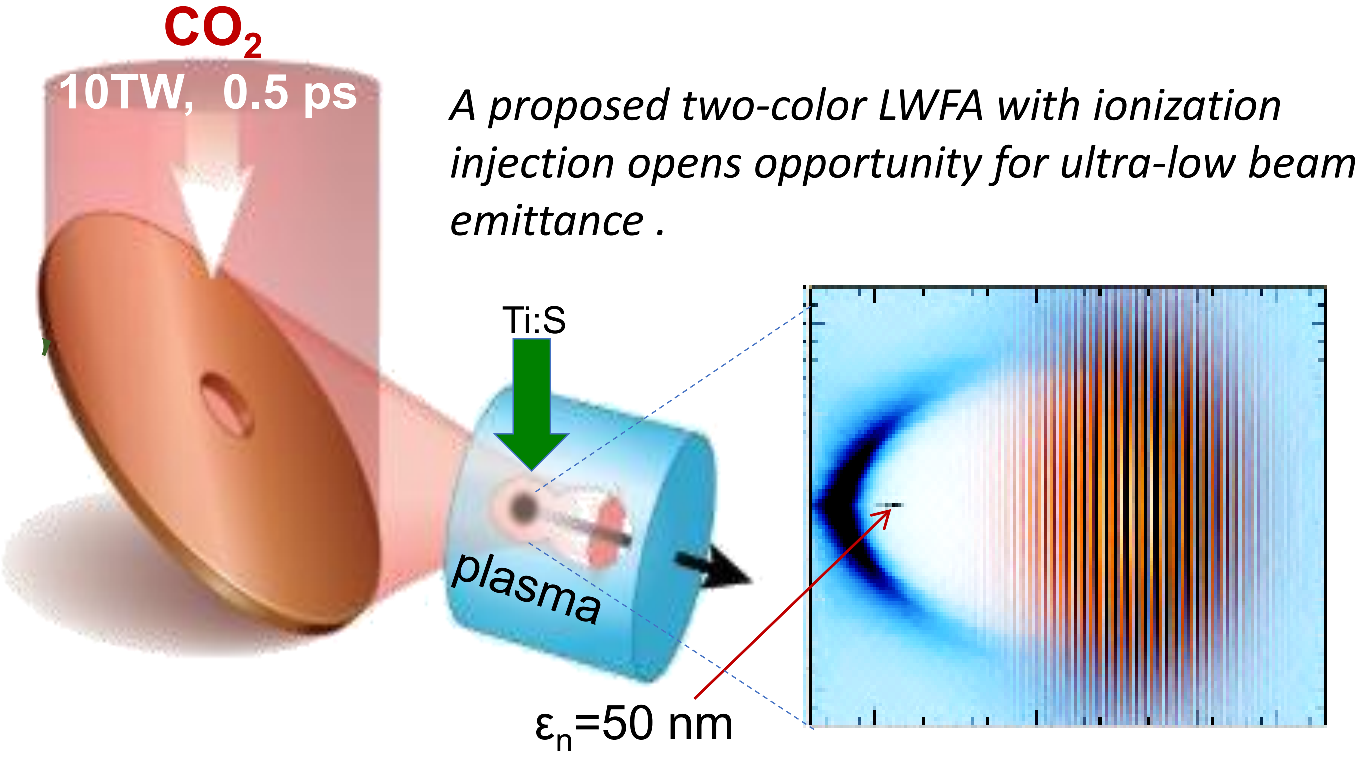
- LWFA regime at low plasma density is of interest because of a bigger bubble size that means
  - the ease of phase space control for
    - ✓ electron injection,
    - ✓ reducing energy spread and emittance
    - ✓ synchronization of acceleration stages
  - higher bunch charge

.

- A CO_2 laser reaches the LWFA bubble regime for the same plasma density, at 100 times smaller laser power and energy compared to a Ti:S laser. This is a direct result from the laser wavelength scaling of an electron's ponderomotive potential

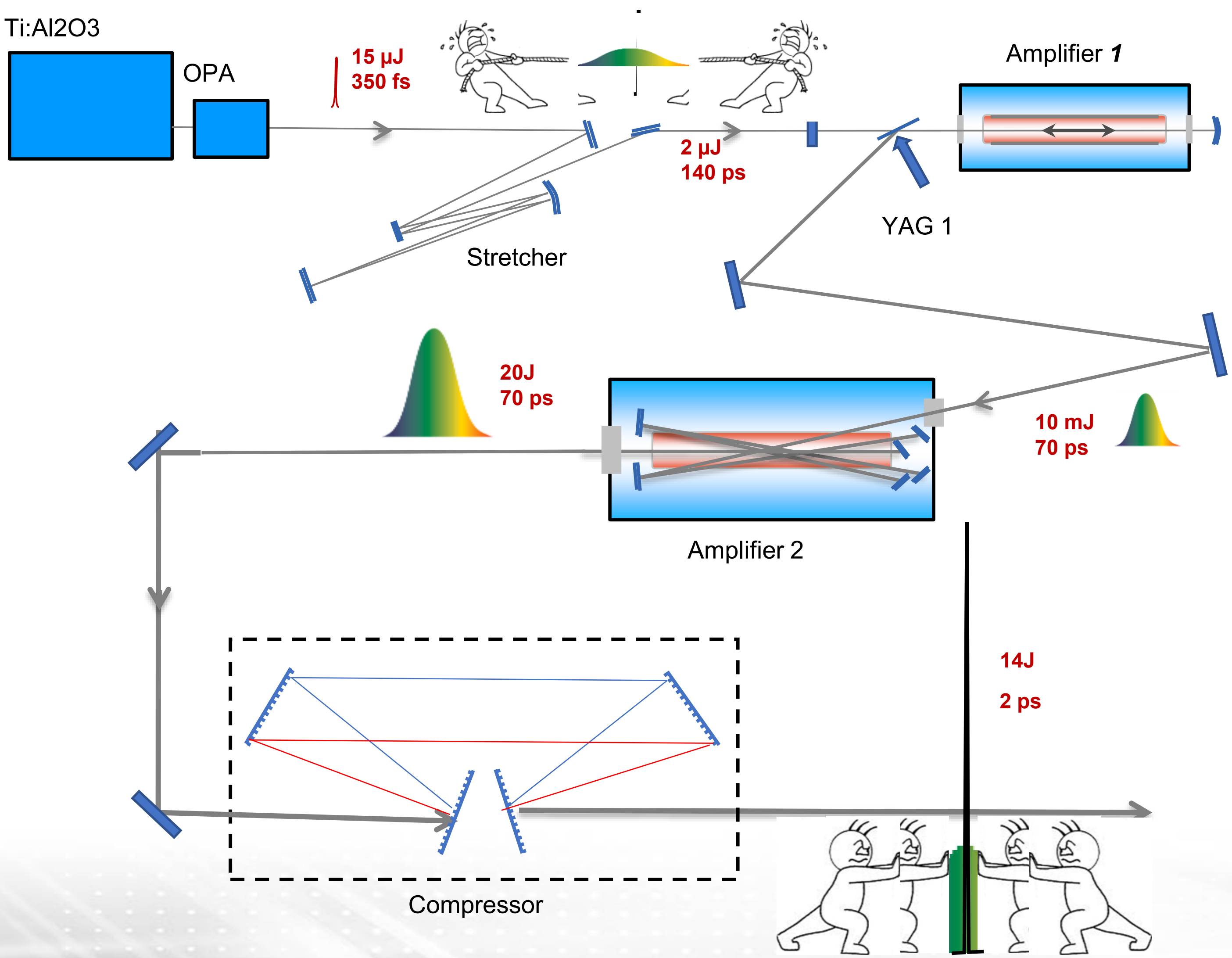
$$\Phi_p = \frac{e^2 E^2}{4 m \omega^2}.$$

A proposed two-color LWFA with ionization injection opens opportunity for ultra-low beam emittance .



- Long-λ laser efficiently produces a big (~300 μm) bubble.
- Short-λ laser provides precision ionization injection.
- As Φ_p for short-λ laser is small, injected electrons are cold and emittance is low.
- Existing proposals call for >10 TW, ~0.5 ps CO_2 pulses.

State of art in CO_2 laser technology



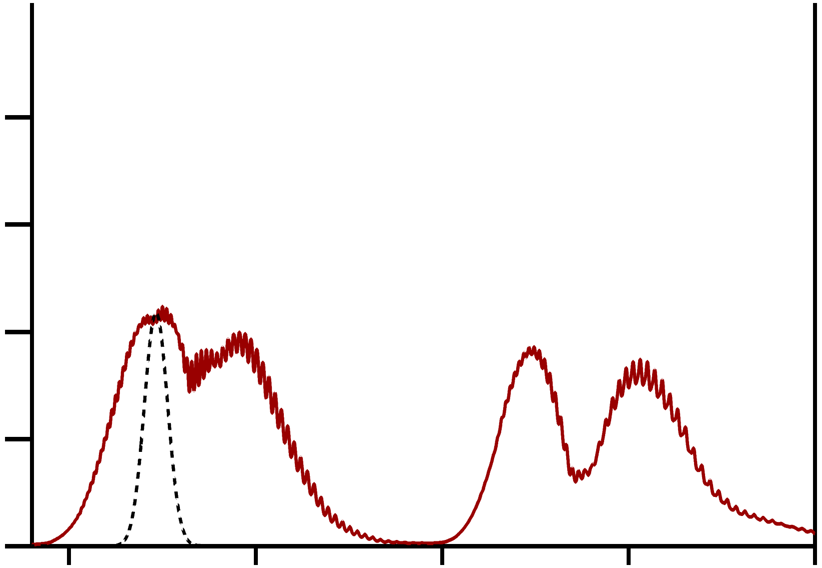
ATF LWIR Laser System

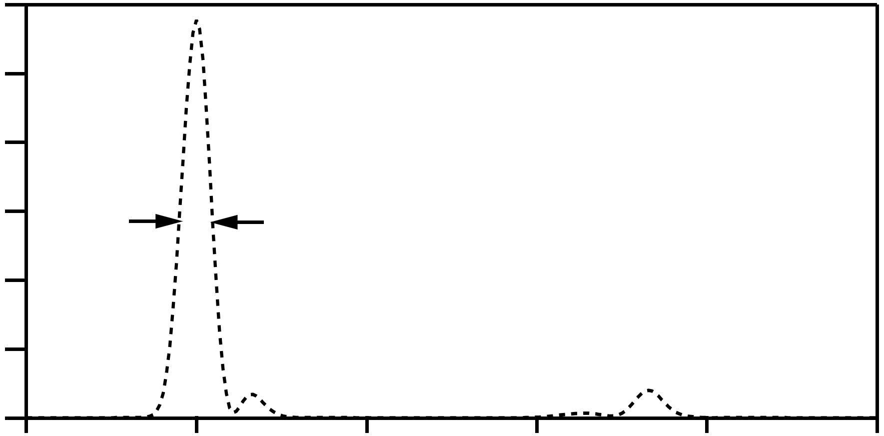
- Solid-state OPA front end followed by two CO_2 electric discharge amplifiers.
- Recently demonstrated upgrade - first **CPA** CO_2 laser system.
- CPA method allows to reach 5 TW in 2 ps by reducing B-integral<1 on the amplifier's output window.

M. P. Polyanskiy, I. V. Pogorelsky, M. Babzien and M. A. Palmer, "Demonstration of a 2 ps, 5 TW peak power, long-wave infrared laser based on chirped-pulse amplification with mixed-isotope CO_2 amplifiers", *OSA Continuum* **3** 459 (2020).

Can we do better than 2 picoseconds?

- Gain spectrum allows to amplify 500 fs pulses.
- However gain narrowing over >7 decades of amplification brings the pulse to 2 ps.





Possible routes to ultra-fast CO_2 pulses:

- The 500 fs pulse duration will be preserved if we get a 10-mJ femtosecond front end (OPCPA?).
- Another option is the nonlinear post-compression (NLPC) reported here.

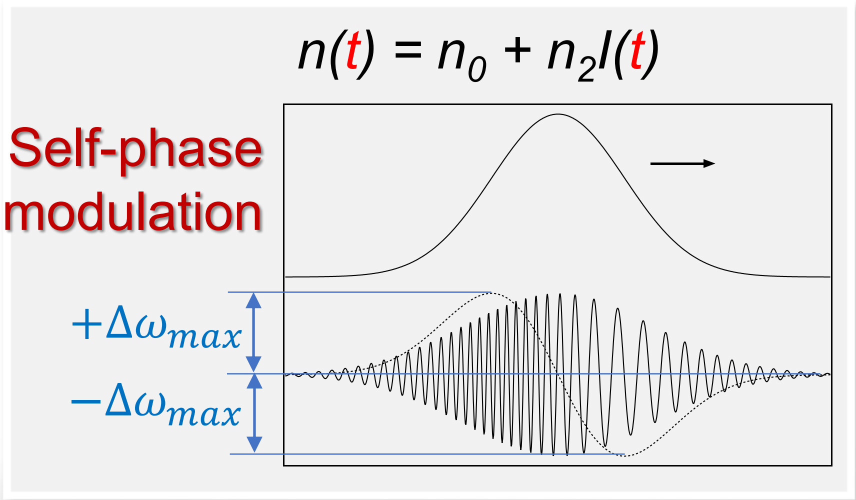
Principle of nonlinear post-compression

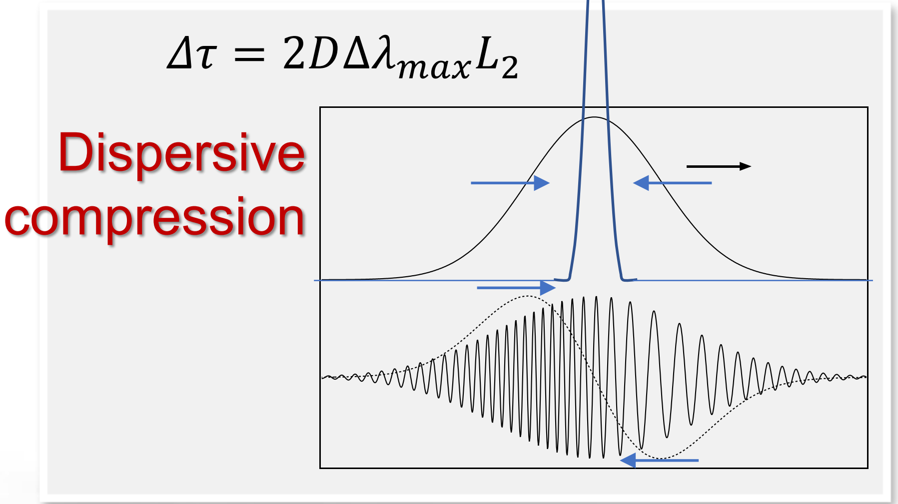
- The method of nonlinear post-compression in bulk solids and optical fibers is known in solid-state laser technology for decades.

C. Rolland and P. B. Corkum, "Compression of high-power optical pulses", *J. OSA* **B 5** 641-647(1988)

M. Nisoli, S. De Silvestri, and O. Svelto, "Generation of high energy 10 fs pulses by a new pulse compression technique", *Appl. Phys. Lett.* **68** 2793 (1996)

- Two steps:
  - Self-phase modulation due to Kerr effect in a nonlinear material results in a quasi-linear frequency chirp.
  - A chirped pulse gets compressed in a material with a group dispersion of the opposite sign.





$$\Delta\omega_{max} = -\left(\frac{\omega_0}{c}\right) n_2 L_1 \frac{I_0}{\tau}$$

Similar method was proposed for CO_2 laser

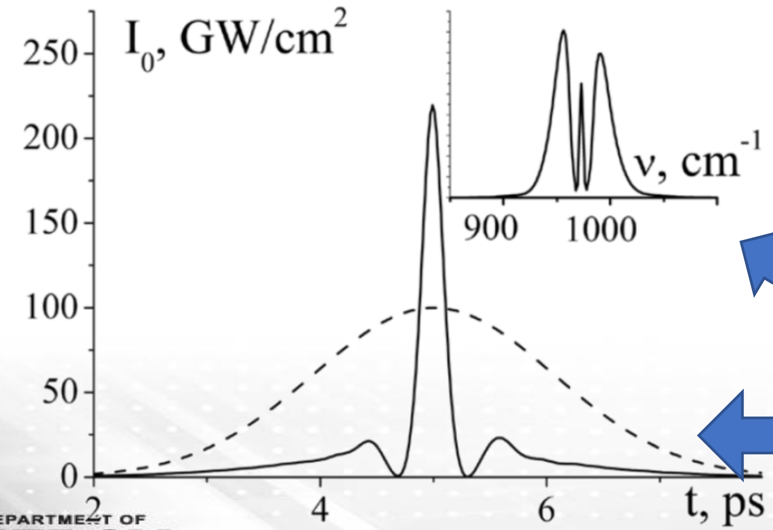
IOP Publishing | Astro Ltd — Laser Physics Letters
Laser Phys. Lett. **11** (2014) 065401 (5pp) — doi:10.1088/1612-2011/11/6/065401

Self-compression of terawatt level picosecond 10 μm laser pulses in NaCl

B G Bravy[1], V M Gordienko[2] and V T Platonenko[2]

Proposed and numerically validated was a compression regime of powerful 10 μm laser radiation (power 500 GW, energy of 1.5 J, pulse duration 2.5 ps), taking into account the nonlinear and dispersive properties of the NaCl crystal.

- Here, both steps, chirping and compression, progress simultaneously as the material has both properties: nonlinear refraction and the opposite sign group dispersion.
- This complicates the physical picture and requires numerical simulation

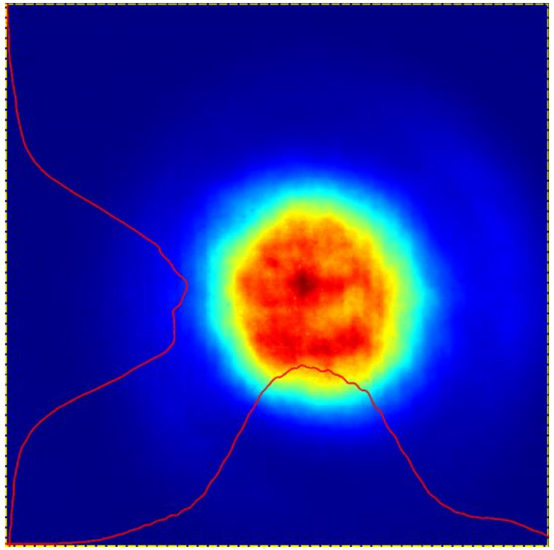


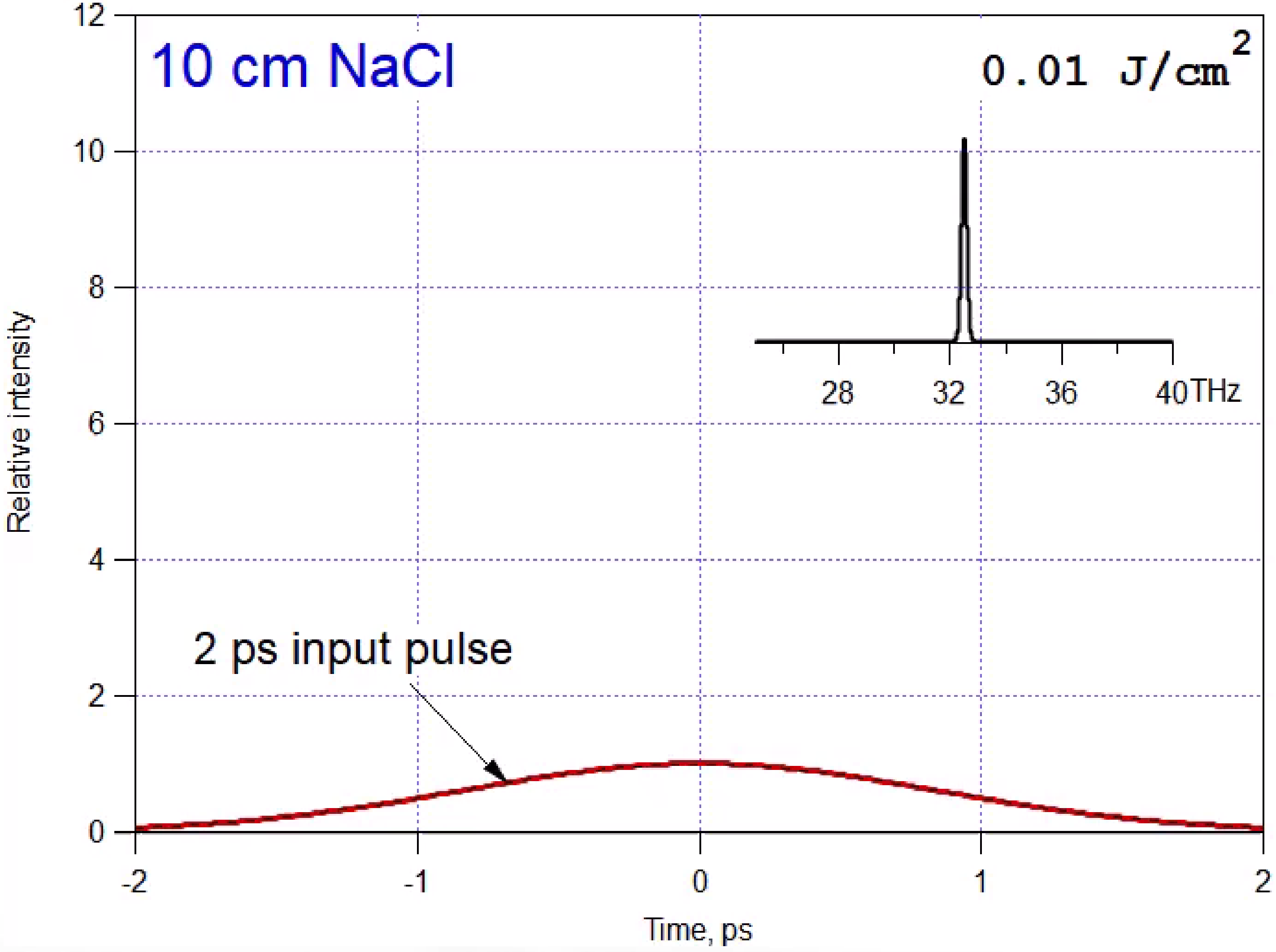
- Input 0.25 J/cm^2
- Total NaCl thickness 19 cm, segmented
- Maximum compression to 250 fs

Pulse and spectrum at maximum compression

Simulations for our initial experiment

- Simulations done in approximation of a flat beam profile.
- Quasi-gaussian beam from the ATF CO_2 laser system.

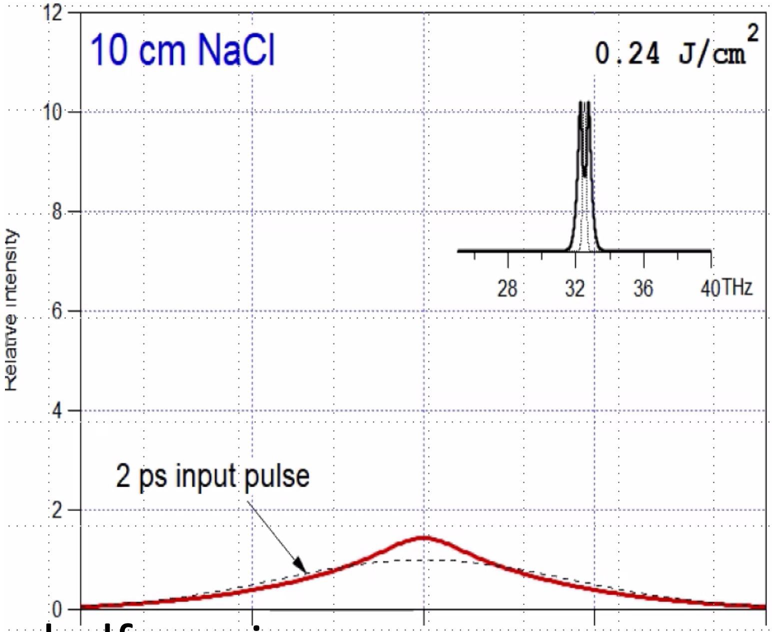




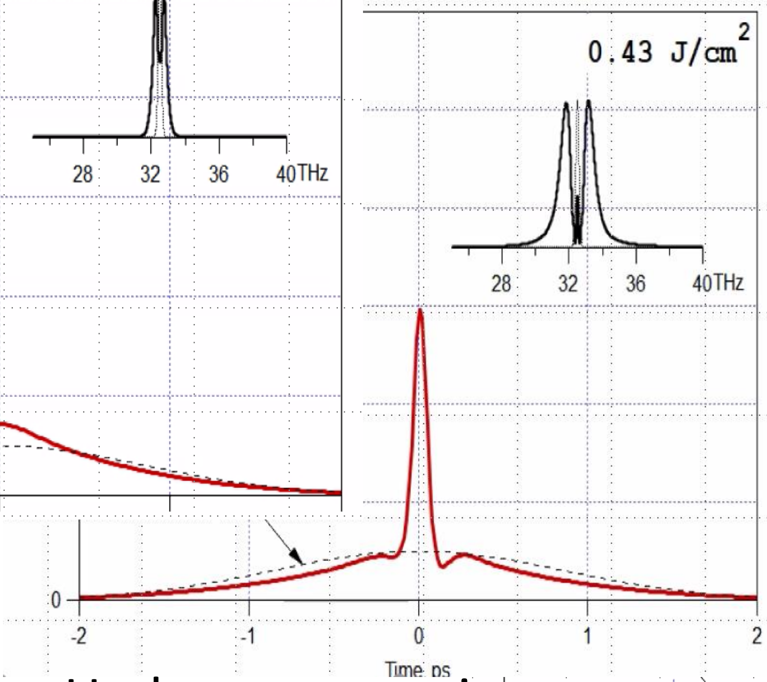
- Down to 100 fs pulse compression predicted.

Simulations for our initial experiment

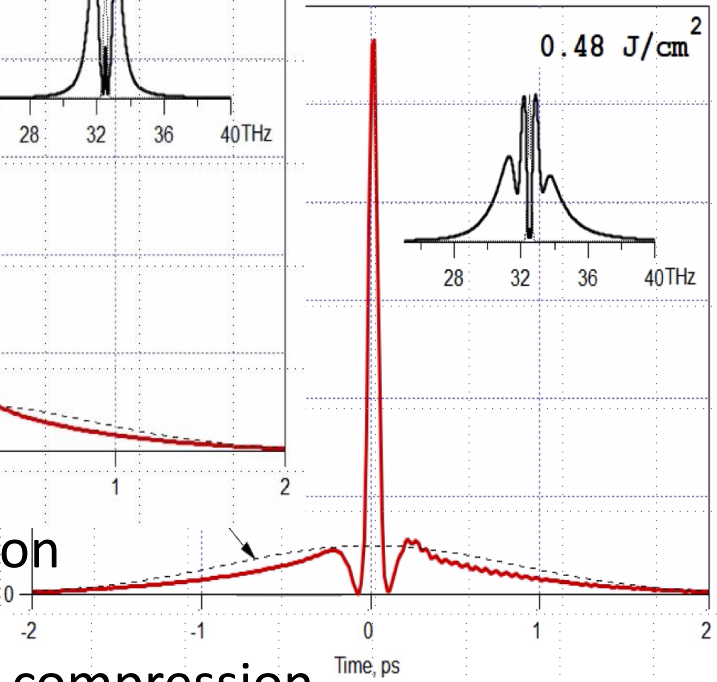
- Note the criticality of getting the optimum fluence.
  - ±10% deviation from the optimum results in >2 times reduction in intensity of the compressed pulse.



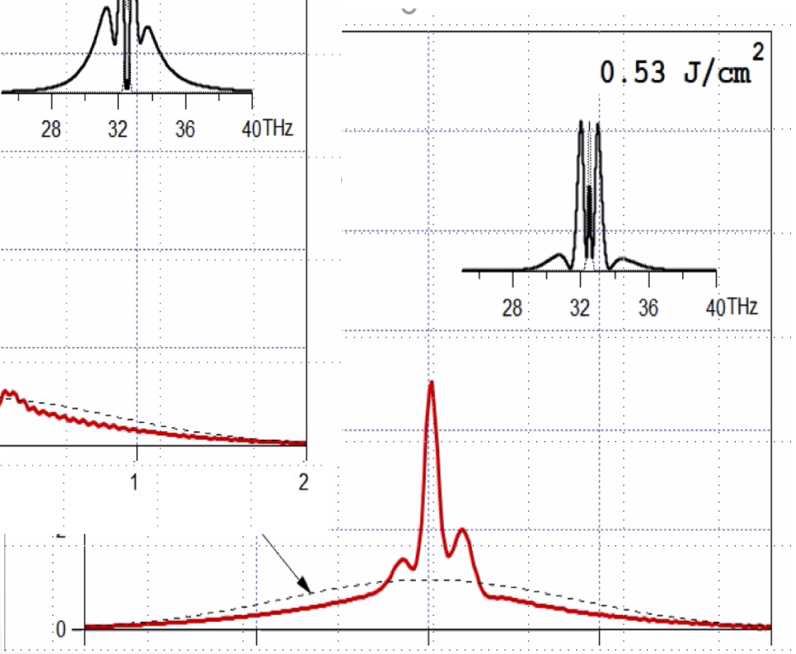
- At the half-maximum input intensity, compression is nearly invisible.



- Under-compression



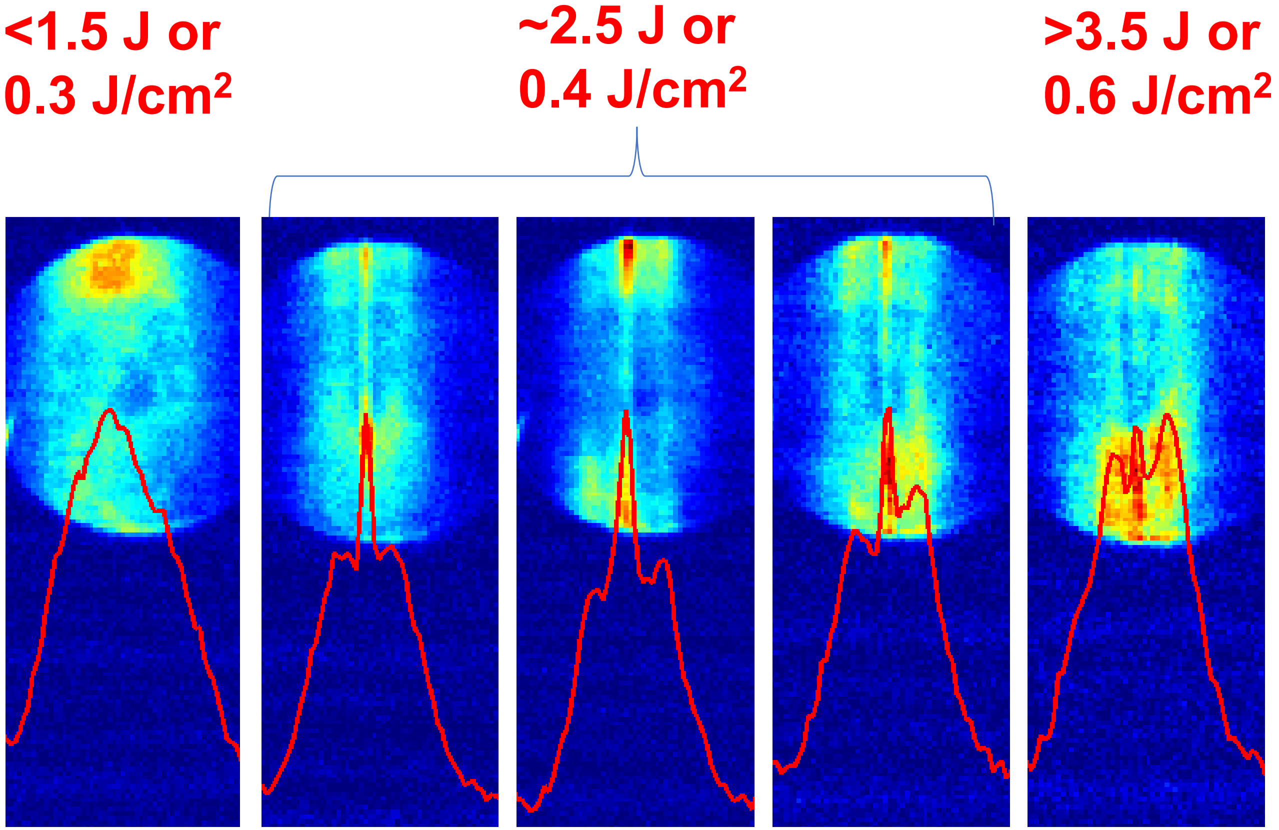
- Best compression to 100 fs



- Over-compression

Our experimental results

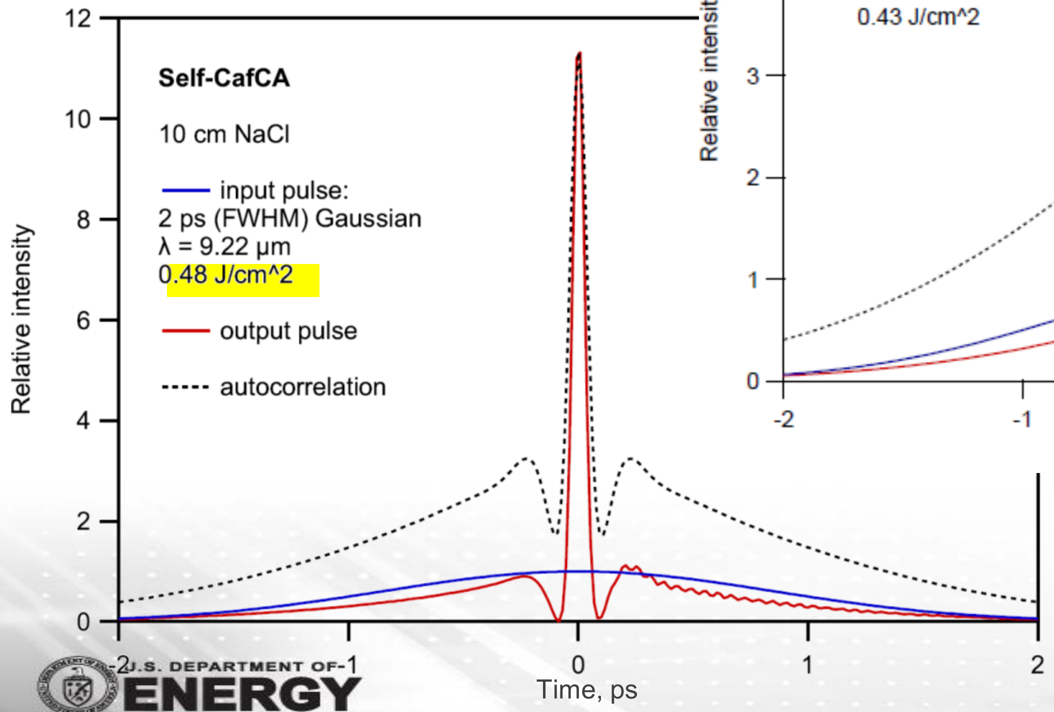
- In experiment, we sent our 2-ps pulse through 10 cm of NaCl and measure the transmitted pulse with a single-shot autocorrelator.
- We systematically observe down to 130 fs pulse structure at the optimum input energy.
- The observed trend of the femtosecond pulse disintegration away from the optimum laser energy agrees with simulations.
- The observed pulse pedestal looks discouraging until we recall that it is enhanced by the autocorrelation function (see next slide).

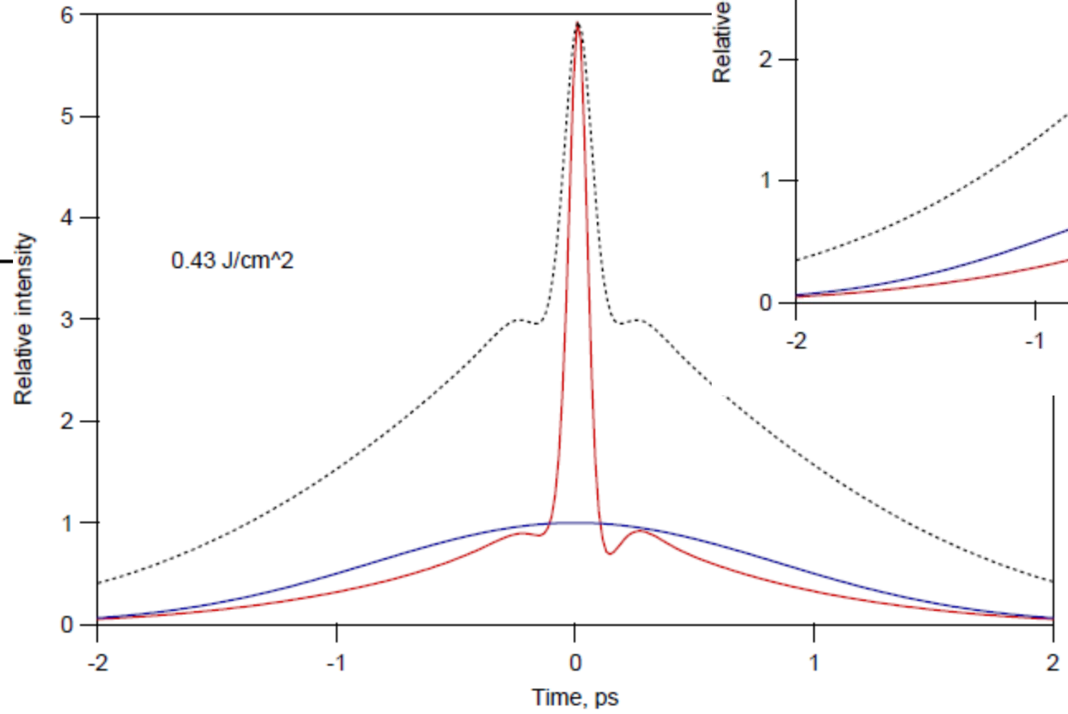


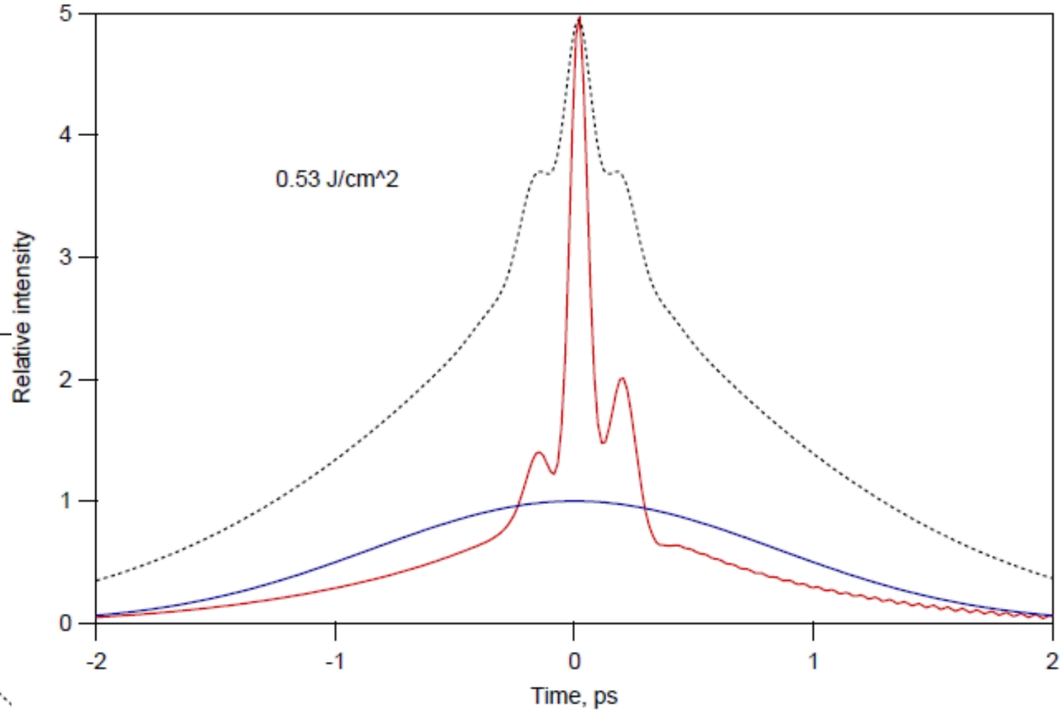
Autocorrelation images versus initial laser energy

More simulations

Compressed pulses and their autocorrelation functions



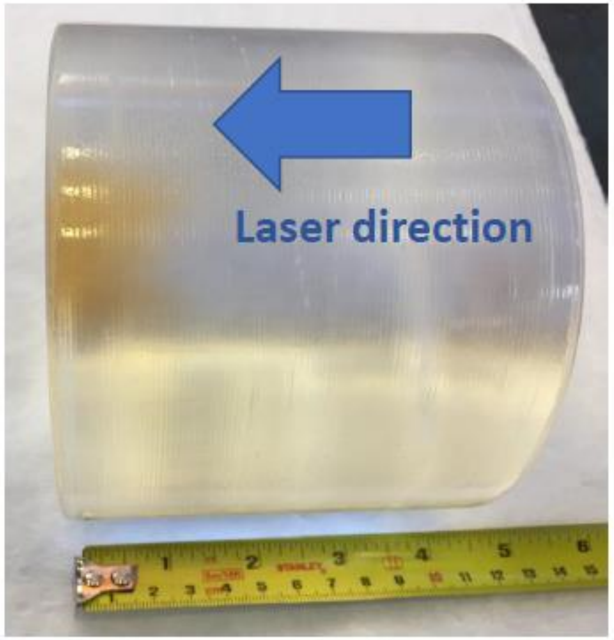


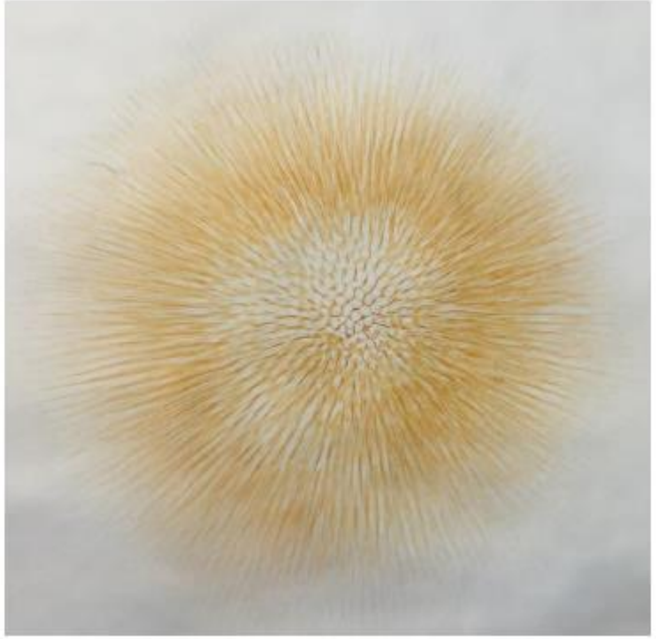


- We see that a real contrast is much higher than seen in autocorrelation

Path to improvement

- B>1 is needed to see the pulse compression.
- However micro-filamentation and color center formation may hinder the process.
- We may suppress micro-filamentation by segmenting the nonlinear material.
- Possibility for further improving efficiency of energy conversion to femtoseconds is being explored via <u>combination of materials.</u>



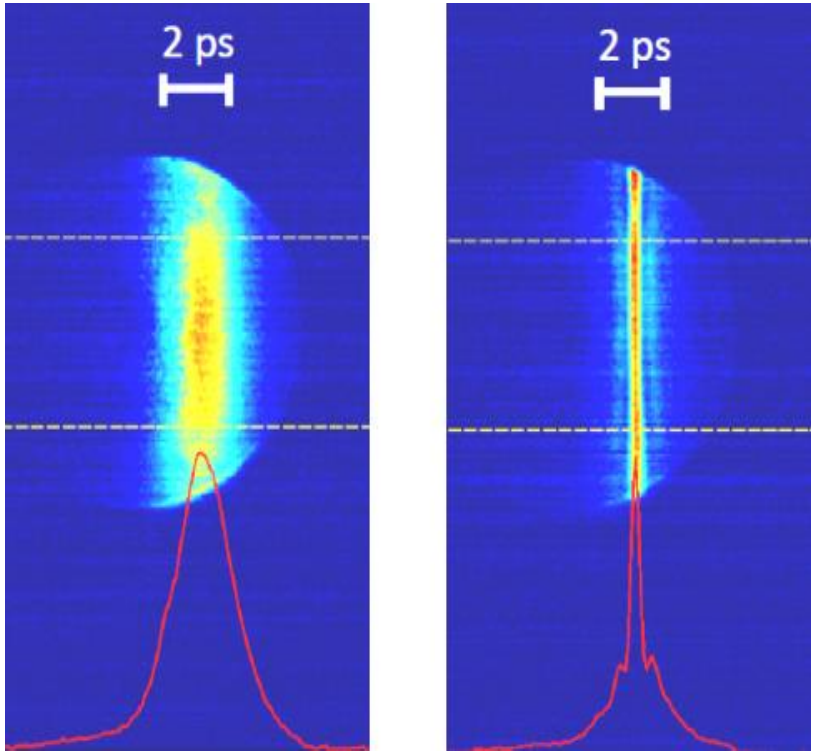


- 1^{st} stage KCl (high n_2, low D)
- 2^{nd} stage BaF_2 (low n_2, high D)

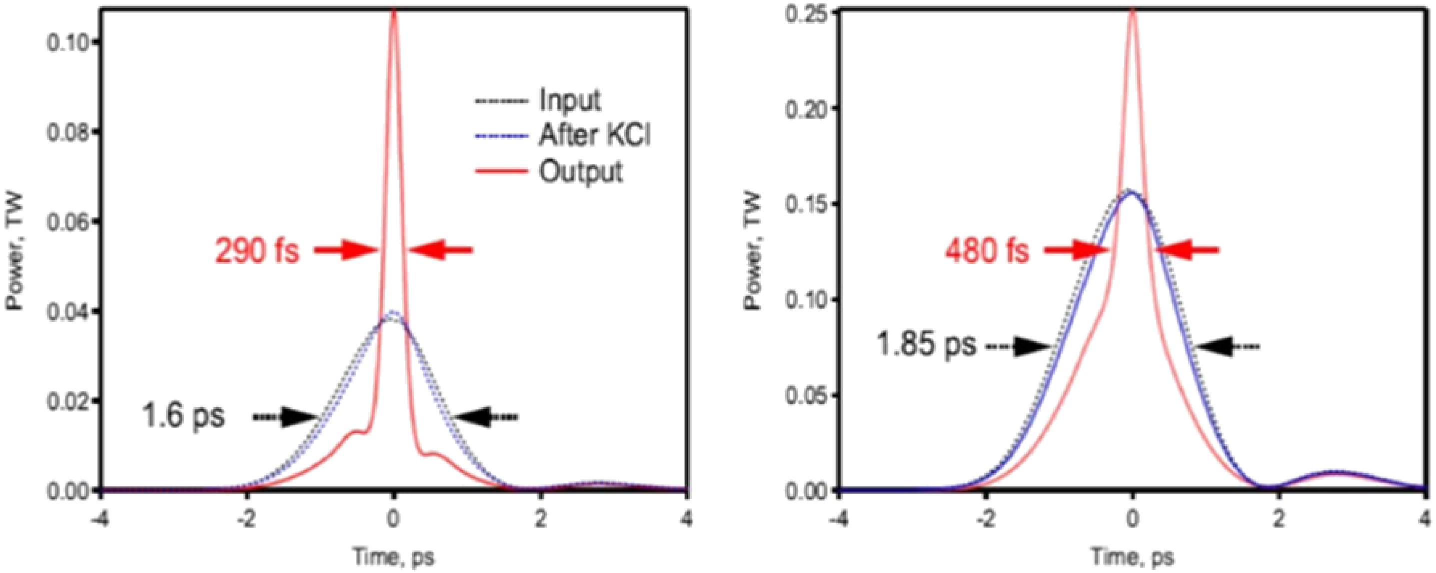
(see next slide)

Two-stage compressor

tested with 100 GW gaussian beam



Autocorrelation images obtained at 450 mJ/cm² incident laser peak fluence without post-compression (left) and with a two-element KCl+BaF_2 compressor, both 5 cm thick (right).



Results of numerical modelling of the pulse compression in the KCl+BaF_2 configuration at the conditions corresponding to the optimum compression;
left – input and output temporal profiles of a 5 mm dia. central portion of a laser beam;
right – the same but integrated over the entire beam.

1:4 compression with 2:1 peak power gain

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SUMMARY

- We report a proof-of-principle experiment on nonlinear pulse compression from 2 ps to femtoseconds in the LWIR spectral domain.
- 130-fs, 9.2-μm pulses have been demonstrated with a single 10-cm NaCl compressor slab.
- A high-contrast, efficient compression to 500 fs has been achieved in a combination of a 5-cm KCl (chirper) and 5-cm BaF2 (compressor)
- The observed effect of pulse compression agrees with simulations.
- Experiments will continue at a 5 TW power.

Thank you!

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