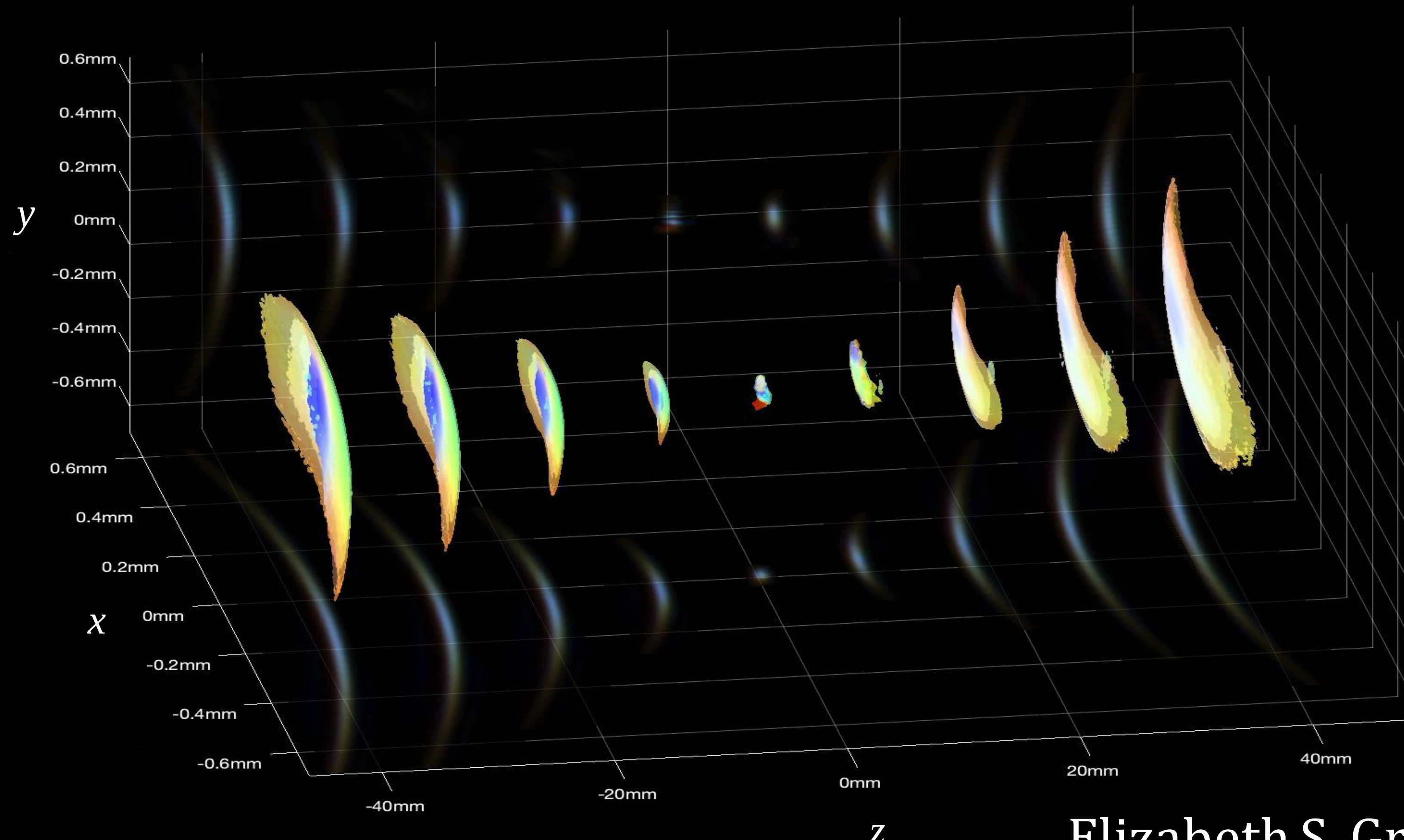
On-shot spatiotemporal laser wavefront characterization via wavelength-multiplexed holography for precision control of high-intensity laser plasma interactions



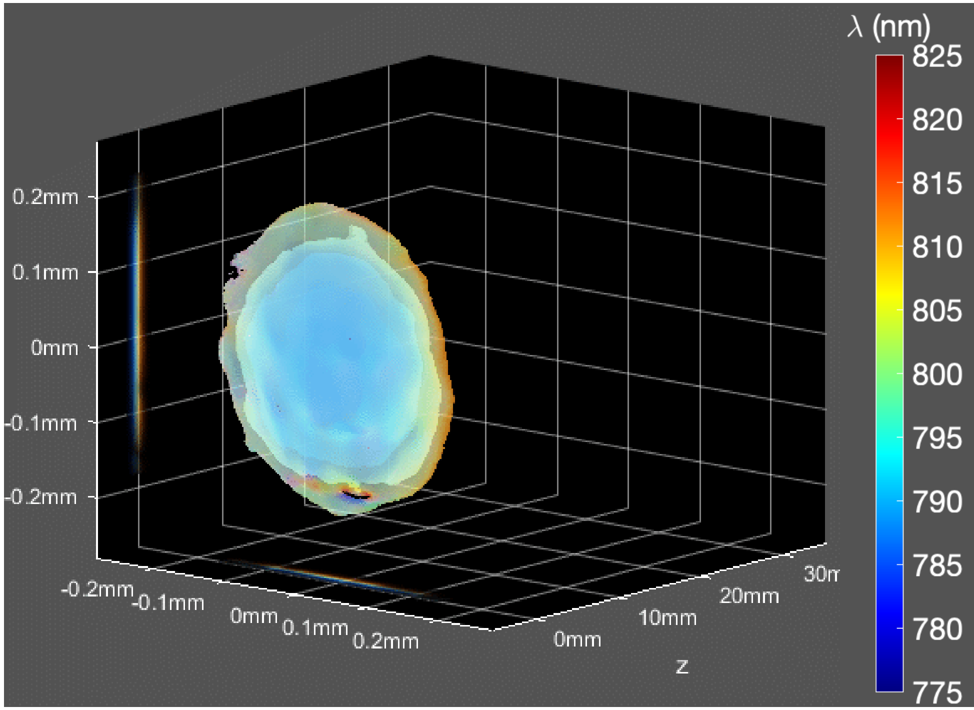
Elizabeth S. Grace

HEDS Center Seminar

February 9, 2023

Ultrafast laser pulse measurements are needed to truly understand the target physics and to have predictive capability.

- Characterization of the complete 4D electric field *E(x,y,z,t)* of the short-pulse (<10ps) laser on a single shot is difficult.
- Most laser-plasma experiments and simulations rely on Gaussian assumptions of the laser's spatial and temporal shape.
- To truly understand the laser-plasma interaction physics, we need complete pulse measurements.
- This work demonstrates high-intensity single shot measurement of *E(x,y,z,t)* and investigates the relationship between laser spatial and temporal structuring and the physics effects downstream.



Measured ultrashort laser pulse with astigmatism and chirp.

This talk covers advances in high-precision laser electric field measurements and control.

- High-intensity, on-shot laser electric field measurement
- Temporal structuring for optimization of laser-driven particle sources
- Spatiotemporal structuring of laser intensity and phase to generate optical vortices

This talk covers advances in high-precision laser electric field measurements and control.

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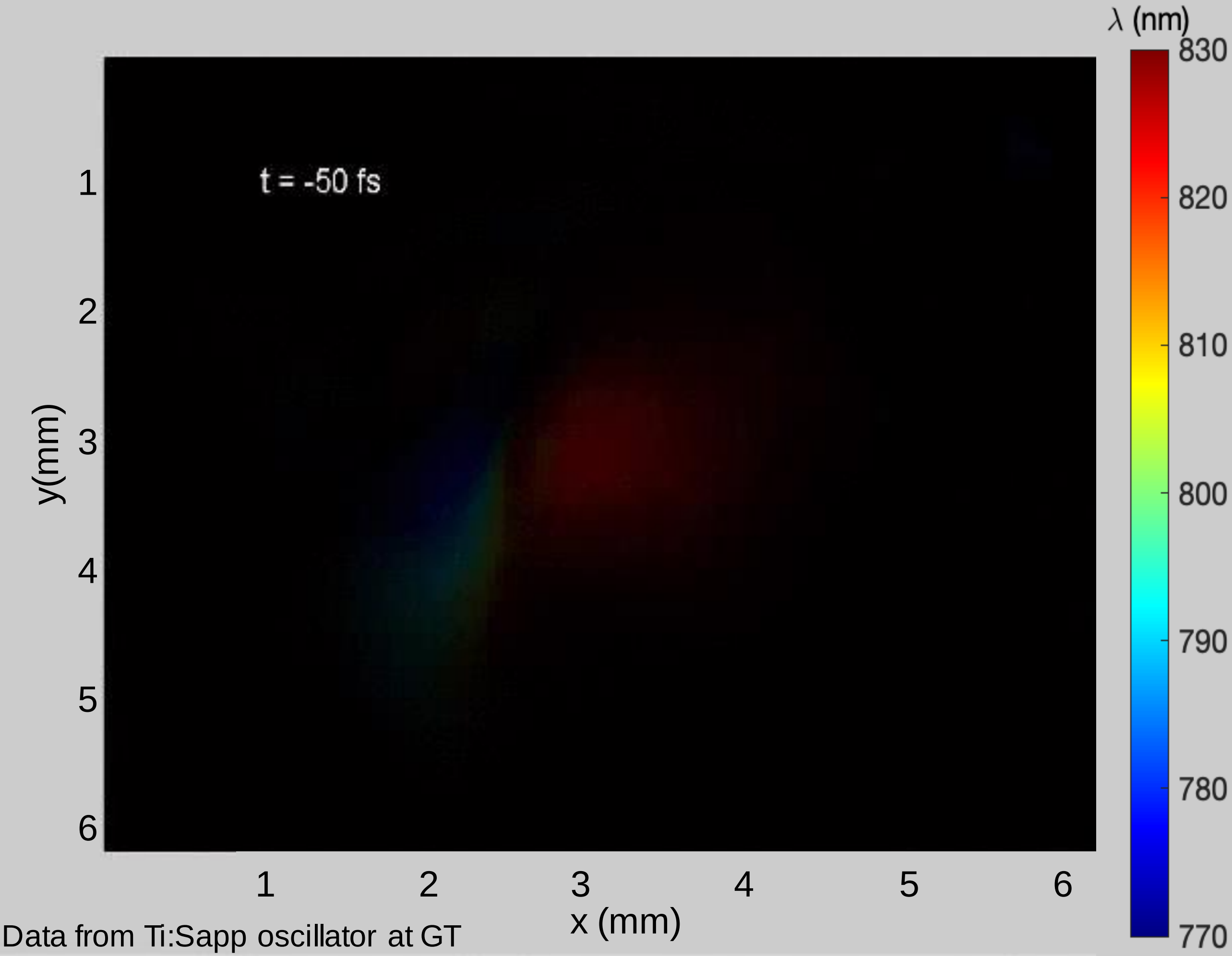


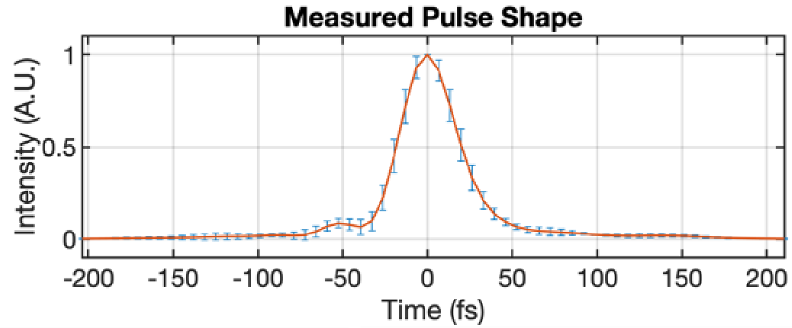
Data from Ti:Sapp oscillator at GT

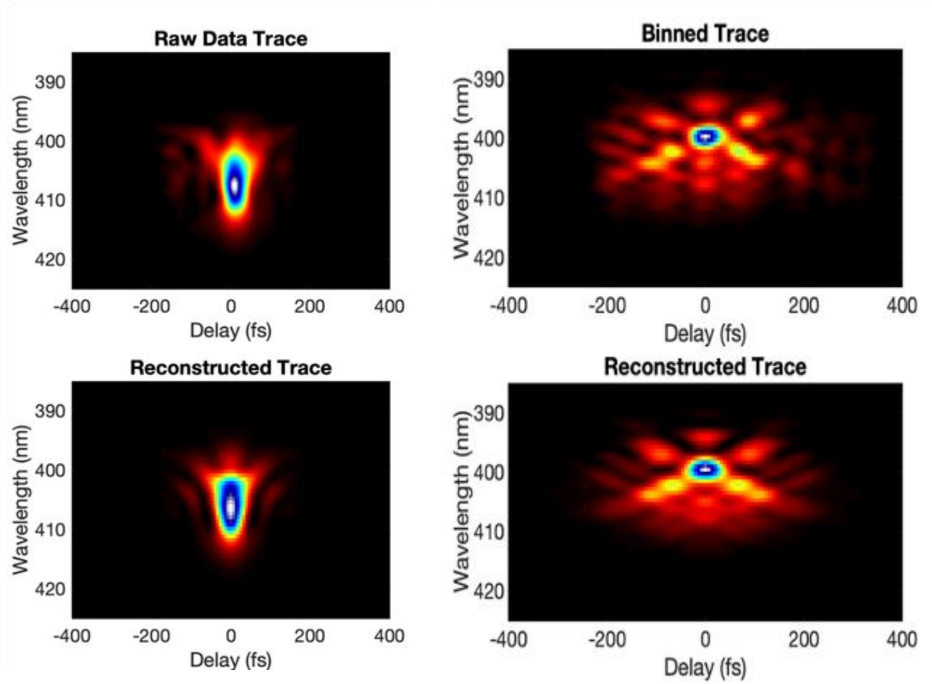
This talk covers advances in high-precision laser electric field measurements and control.

High-intensity, on-shot laser electric field measurement

Temporal structuring for optimization of laser-driven particle sources

Spatiotemporal structuring of laser intensity and phase to generate optical vortices





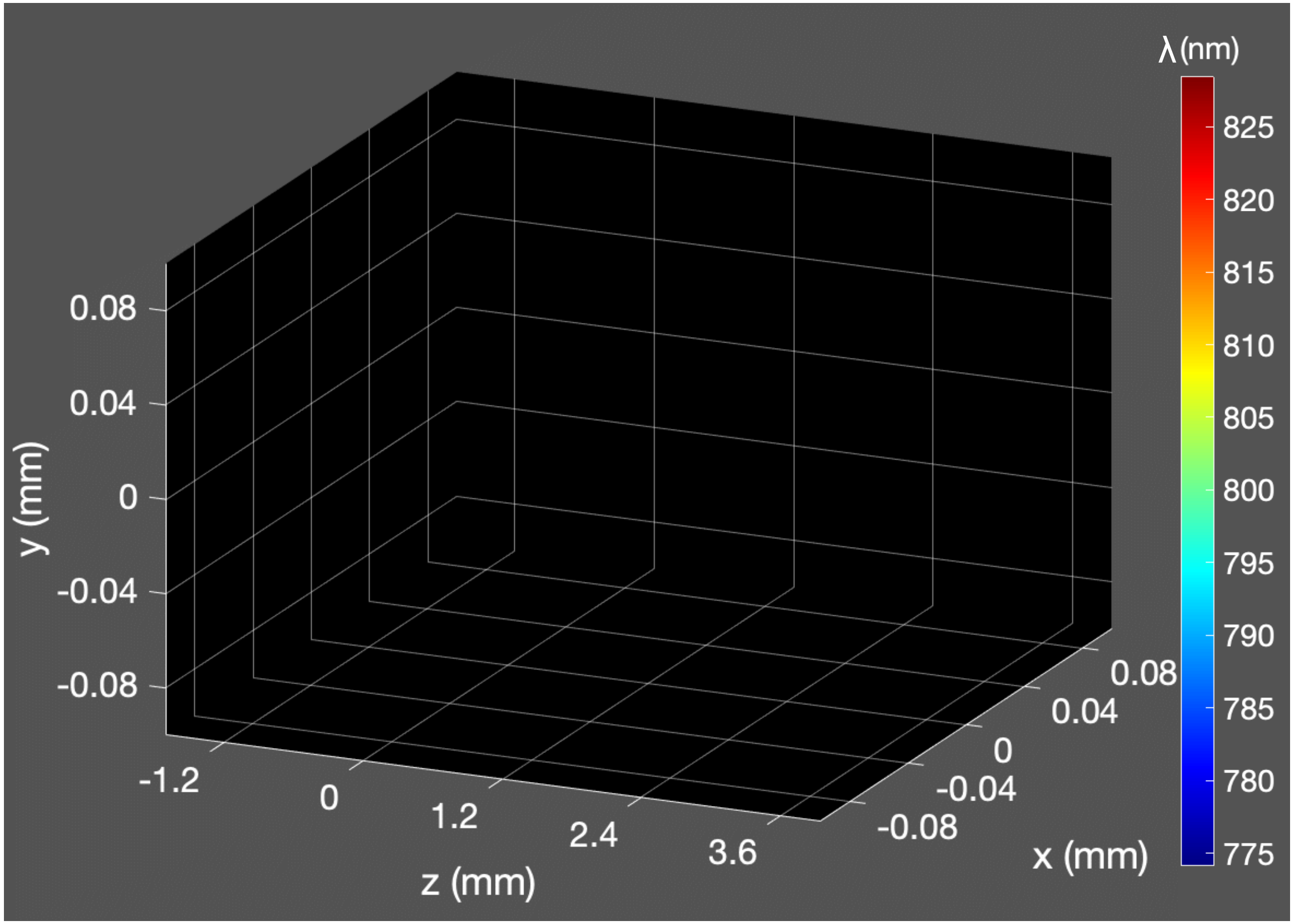
Data from CSU laser system (2021).

This talk covers advances in high-precision laser electric field measurements and control.

High-intensity, on-shot laser electric field measurement

Temporal structuring for optimization of laser-driven particle sources

Spatiotemporal structuring of laser intensity and phase to generate optical vortices



Simulation by E. Grace

Thank you to my collaborators!

UCSD

Joohwan Kim

Georgia Tech

Rick Trebino

LLNL

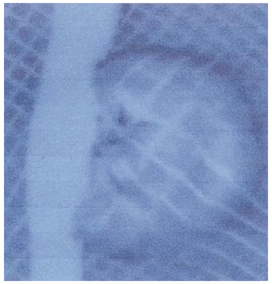
Blagoje Djordjevic
Matt Hill
Andrew Longman
Tammy Ma
Derek Mariscal
Graeme Scott
Raspberry Simpson
Brent Stuart
Kelly Swanson
Scott Wilks
Jackson Williams

CSU

Ghassan Zeraouli

High-intensity laser-plasmas form the basis for many interdisciplinary applications.

Proton Radiography

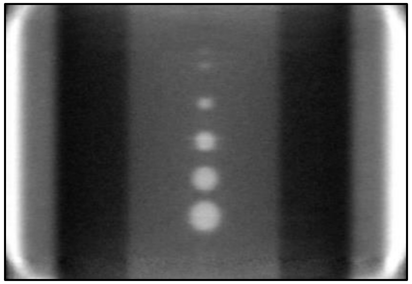


Mackinnon *et al*, RSI (2004).

Laboratory Astrophysics

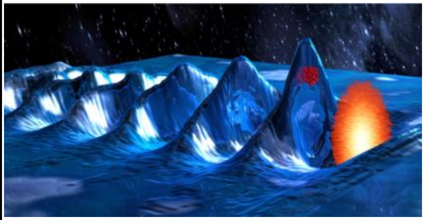
MPIA/NASA/Calar Alto Observatory

Neutron Radiography



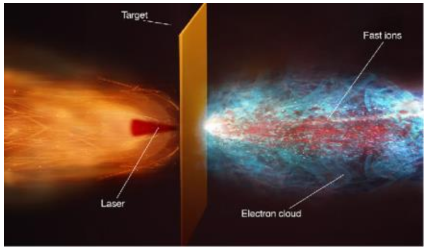
Johnson *et al*, MRP **15** 58-66 (2020)

Electron Acceleration



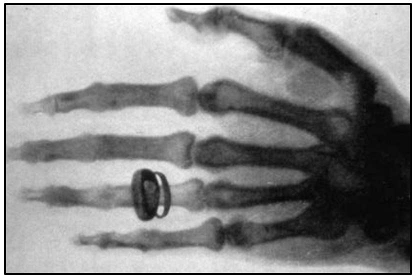
Laboratoire d'Optique Appliquée

Ion Acceleration



Macchi, et al., Rev. Mod. Phys., **85** (2013)

X-Ray Radiography

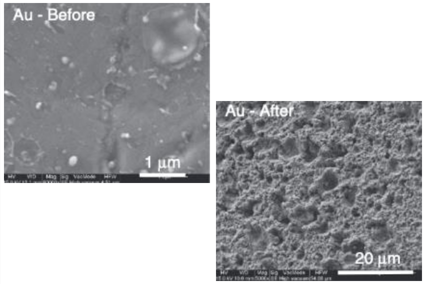


Wilhelm Röntgen, 1895

Medical Radiotherapy

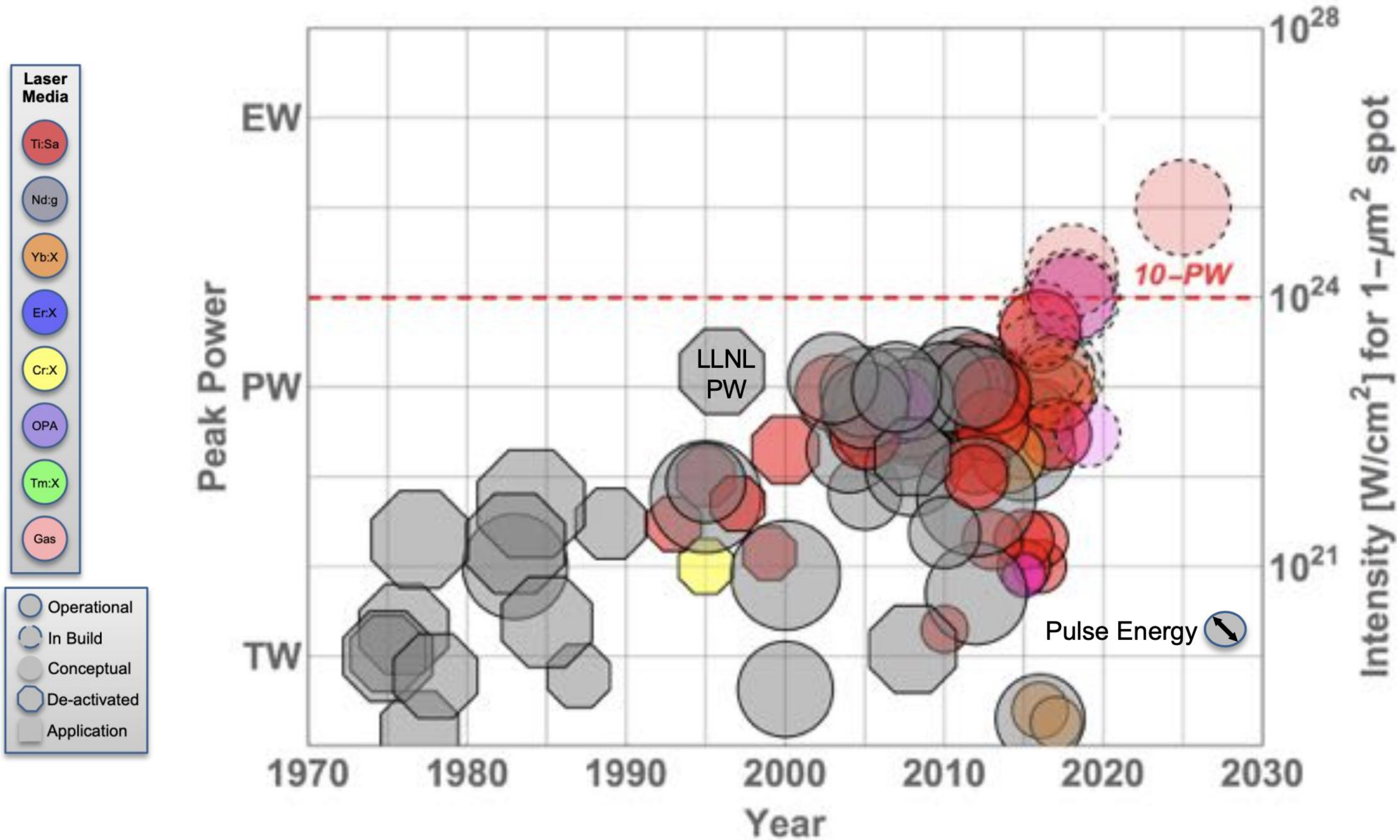
Varian Vitalbeam

Stress Testing



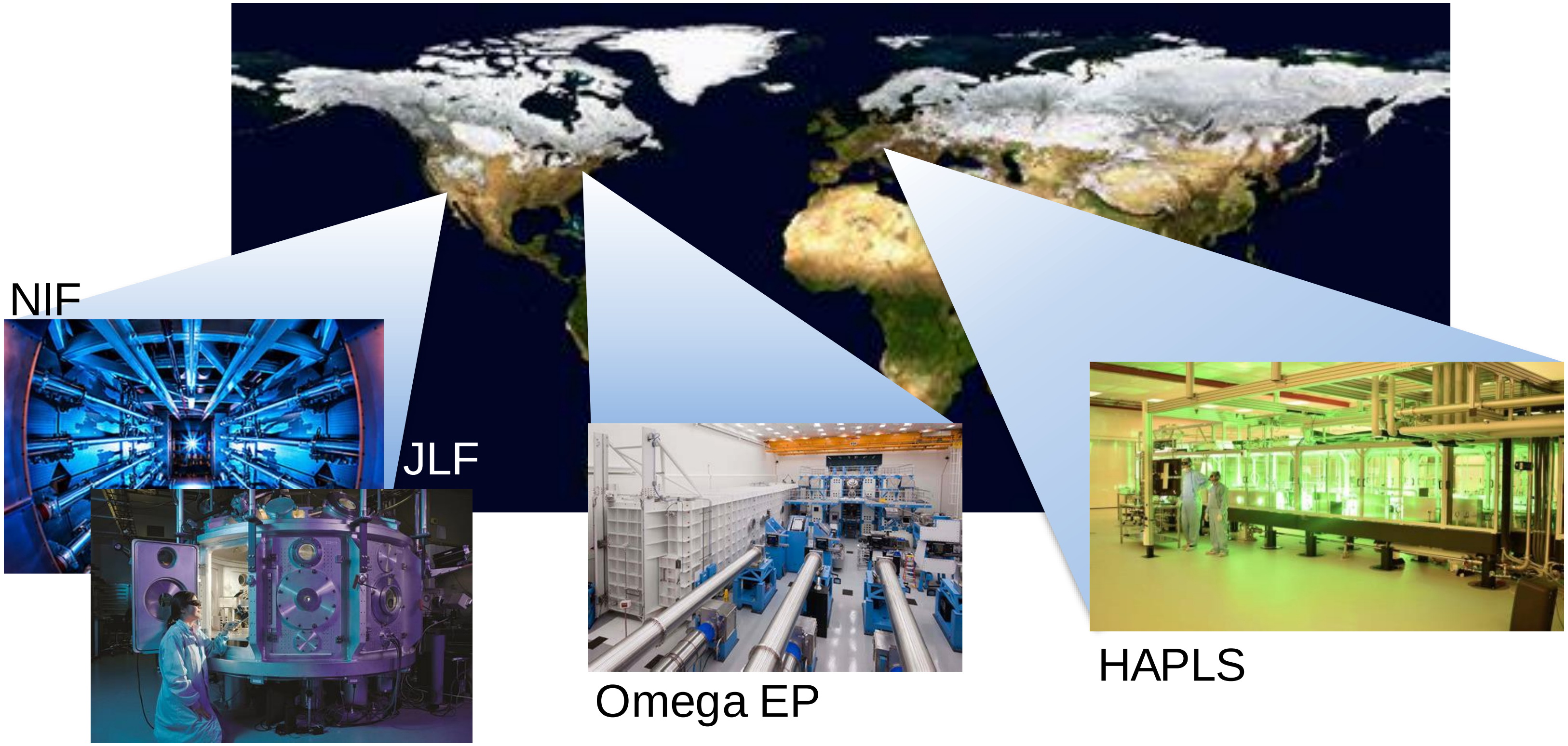
Barberio *et al* Nature (2018)

Around the world, investment in laser technology has produced increased peak powers.



Accurate laser characterization is crucial for every single one of these high-power laser systems but remains a gap.

Livermore is the leader in developing high peak power lasers, and characterization of these lasers is crucial for HED science and other applications.



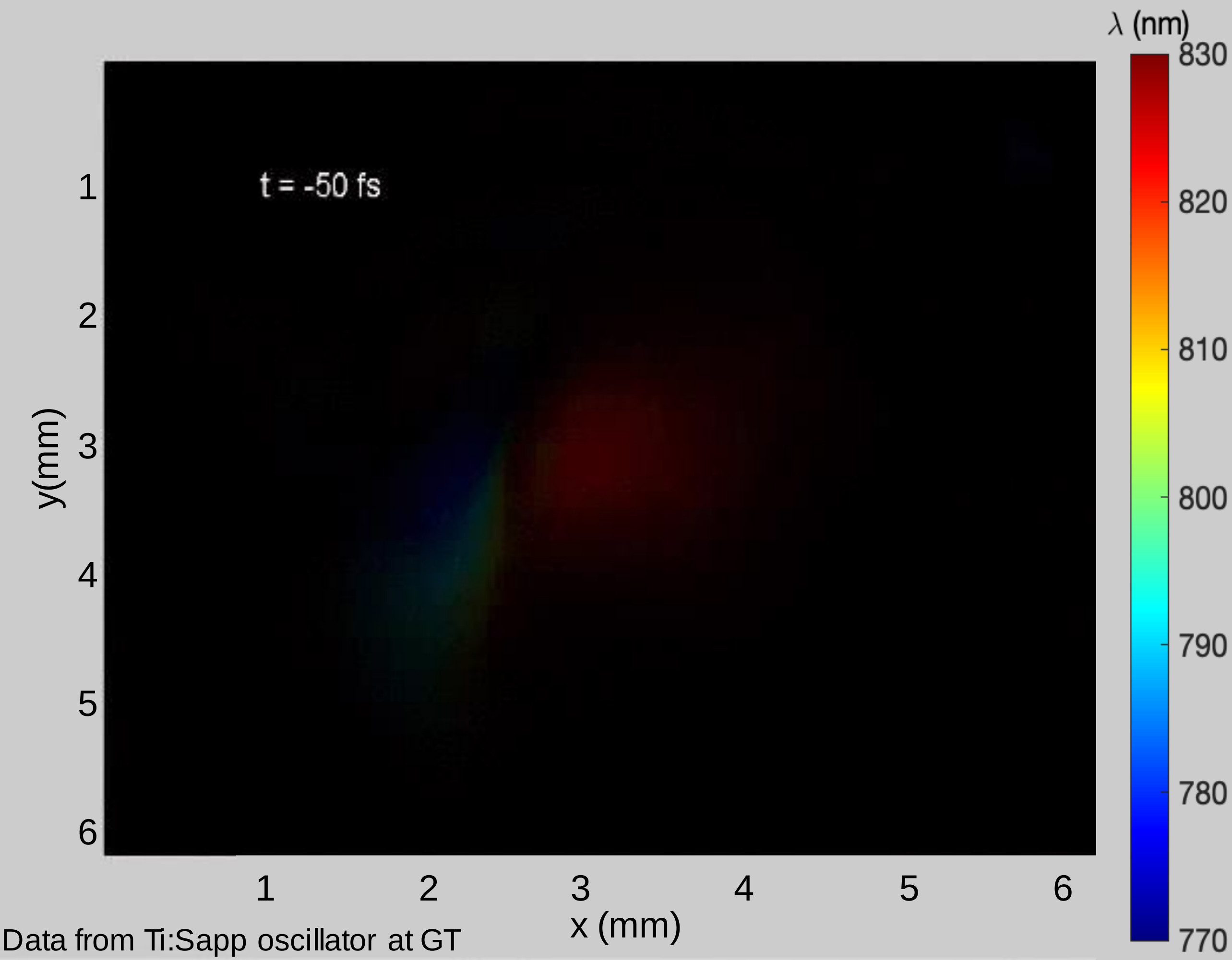
Research with short-pulse lasers is a large part of the HED work at LLNL, from developing predictive capability at ARC to applications like secondary sources.

High-intensity, on-shot laser electric field measurement is crucial.

High-intensity, on-shot laser electric field measurement

Temporal structuring for optimization of laser-driven particle sources

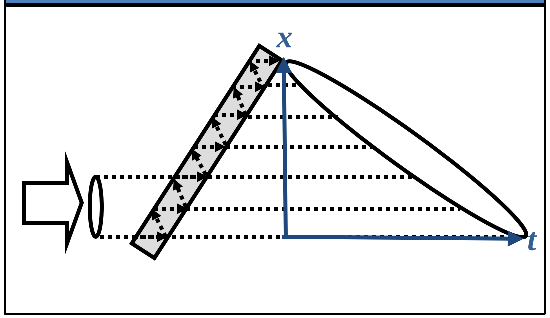
Spatiotemporal structuring of laser intensity and phase to generate optical vortices



Data from Ti:Sapp oscillator at GT

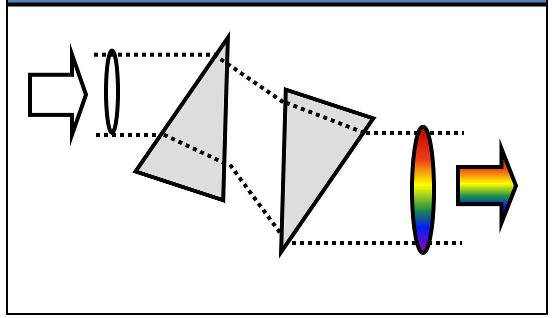
Every ultrafast laser pulse exhibits complex spatiotemporal couplings that are usually not diagnosed.

Pulse-Front Tilt



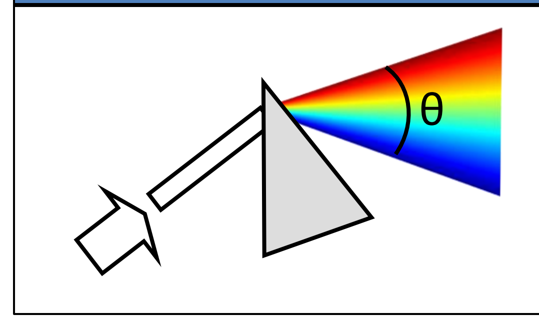
$$E(x,t) \propto \exp(Q_{xx}x^2 + 2Q_{xt}xt - Q_{tt}t^2)$$
$$Re[Q_{xt}] \neq 0$$

Spatial Chirp



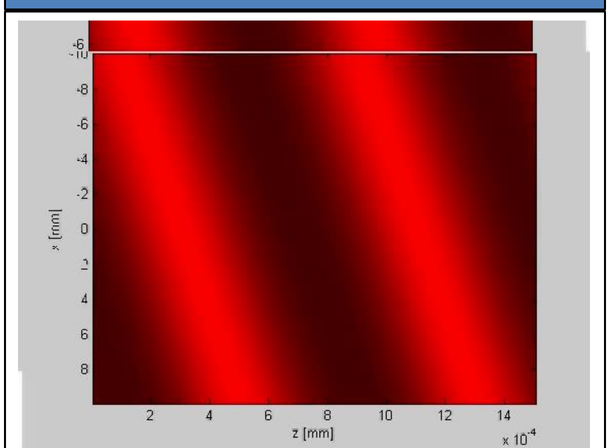
$$E(x,\omega) \propto \exp(R_{xx}x^2 + 2R_{x\omega}x\omega - R_{\omega\omega}\omega^2)$$
$$Re[R_{x\omega}] \neq 0$$

Angular Dispersion



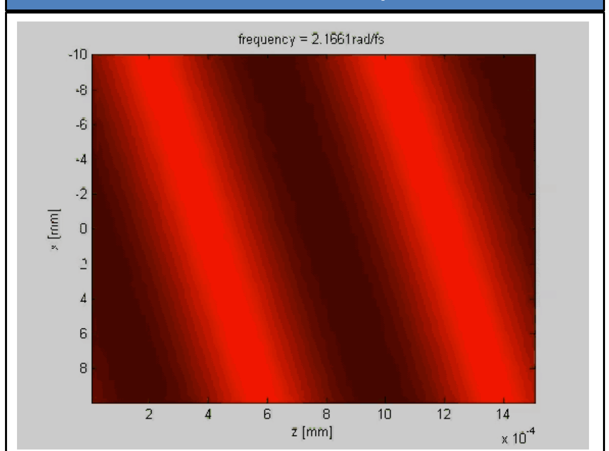
$$E(k,\omega) \propto \exp(S_{kk}k^2 + 2S_{k\omega}k\omega - S_{\omega\omega}\omega^2)$$
$$Re[S_{k\omega}] \neq 0$$

Wavefront rotation



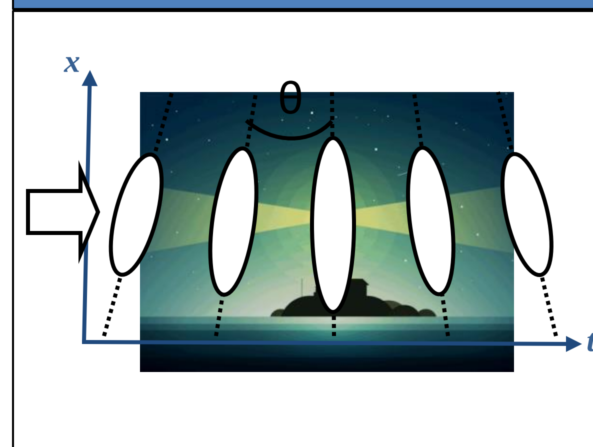
$$E(x,t) \propto \exp(Q_{xx}x^2 + 2Q_{xt}xt - Q_{tt}t^2)$$
$$Im[Q_{xt}] \neq 0$$

Wavefront-tilt dispersion



$$E(x,\omega) \propto \exp(R_{xx}x^2 + 2R_{x\omega}x\omega - R_{\omega\omega}\omega^2)$$
$$Im[R_{x\omega}] \neq 0$$

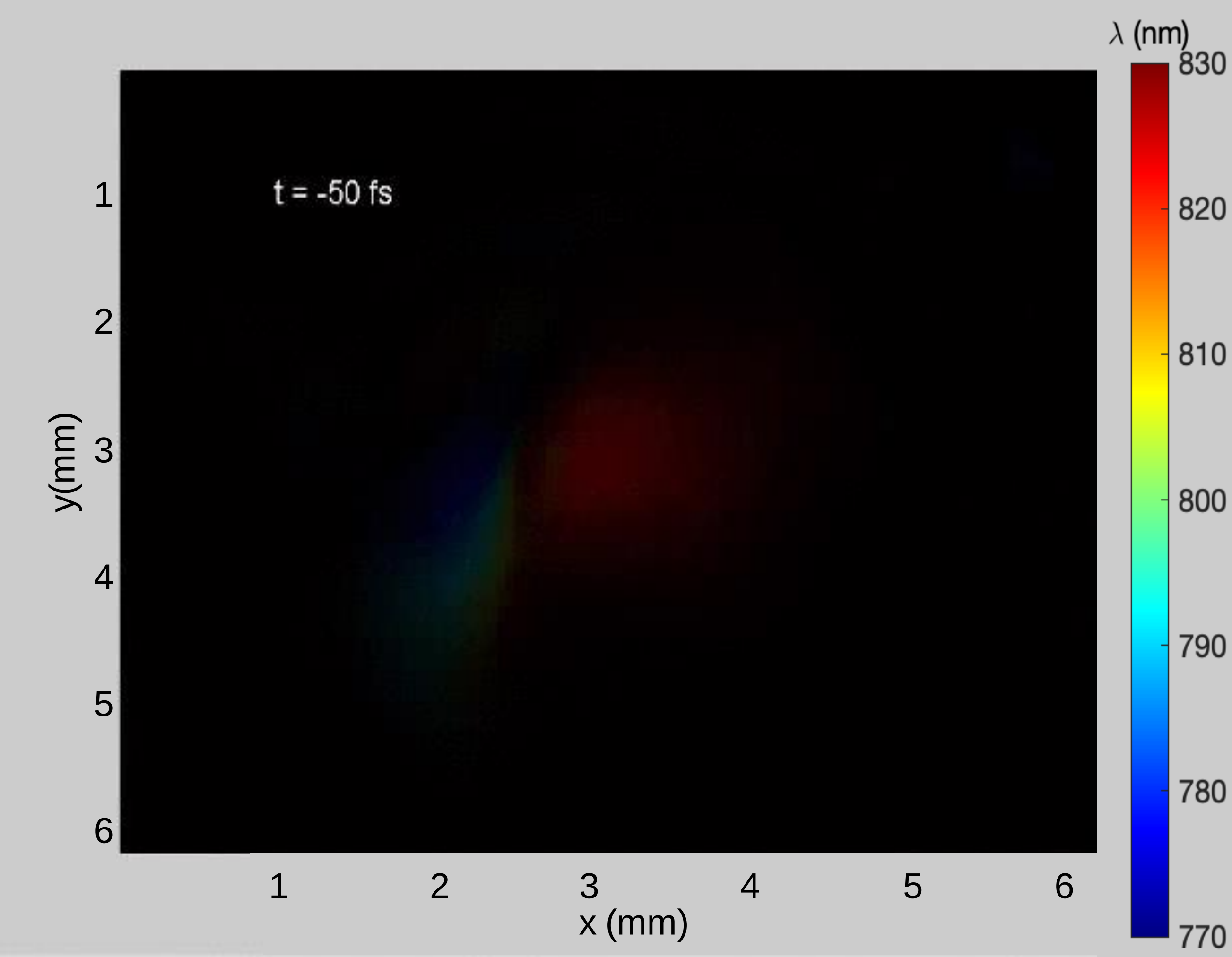
Ultrafast Lighthouse Effect



$$E(k,t) \propto \exp(P_{kk}k^2 + 2P_{kt}kt - P_{tt}t^2)$$
$$Re[P_{kt}] \neq 0$$

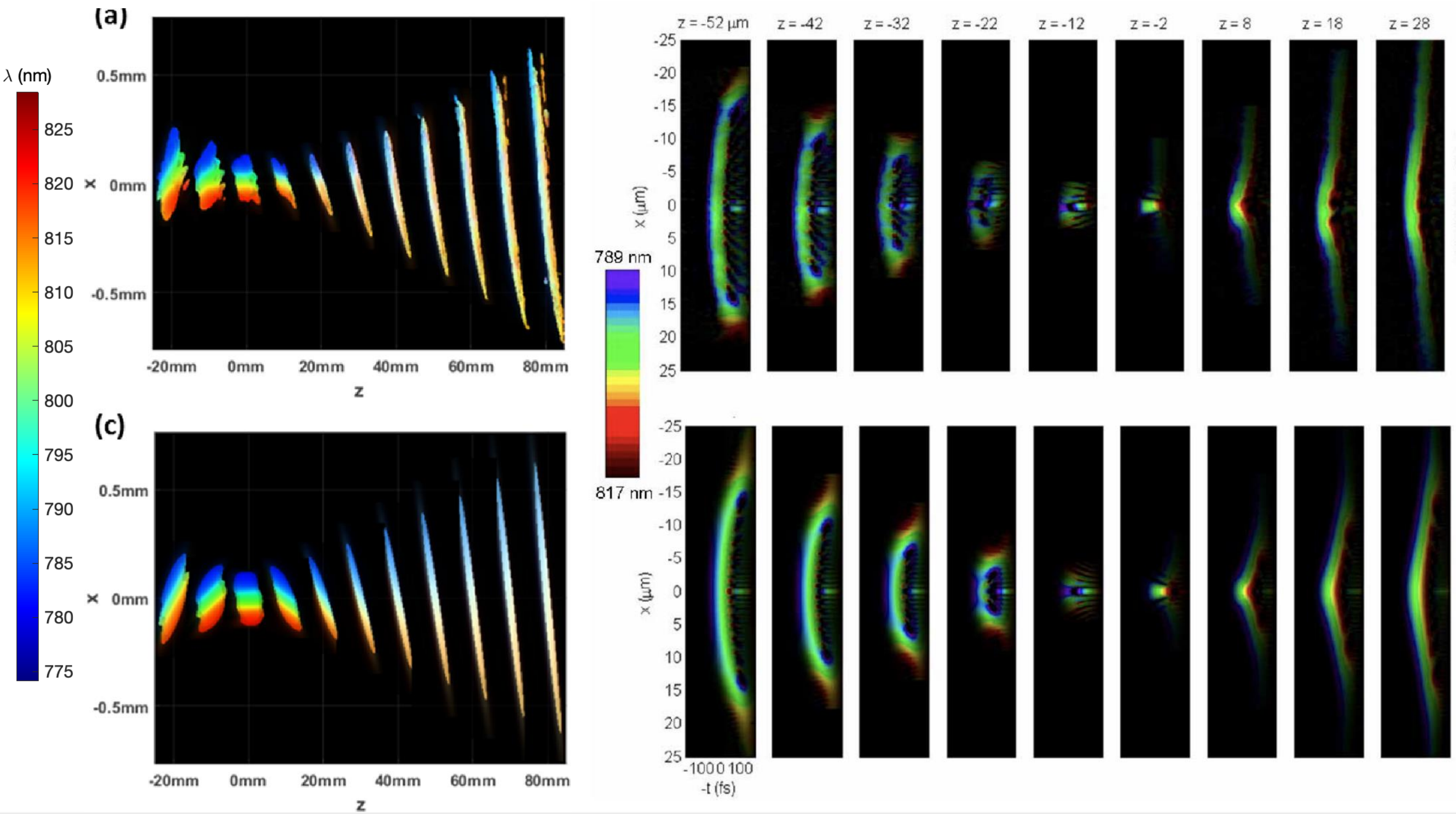
*S. Akturk *et al.*, **13** 21 (2005).

This pulse has temporal chirp, *pulse-front tilt,* and spatial chirp.



*P. Gabolde and R. Trebino, J. Opt. Soc. Am. B **25** A25 (2008)

Spatiotemporal distortions can be very detrimental to applications due to reduced focal spot intensity.



* Z. Guang *et al*. JOSAB **3**:1955-1962(2016).

*P. Bowlan *et al.*, Opt. Express **16** 18 (2008).

Existing pulse measurement techniques generally measure pulses in time only.

- For example, Frequency Resolved Optical Gating (FROG) and its cousin, GRENOUILLE, both capture the intensity and phase of the pulse in time (but averaged over space):

$$E(t) = \mathrm{Re}[\sqrt{I(t)}\ \exp\left[i(\omega_0 t - \phi(t))\right]]$$
$$E(\omega) = \sqrt{S(\omega)}\ \exp\left[-i\varphi(\omega)\right]$$
$$E(\omega) = \mathscr{F}\{E(t)\}.$$

- This is fine if $E(x,y,t) = E(x,y)E(t)$. But the spatial and temporal dependencies may not separate like this.

- Single-shot FROG and GRENOUILLE can also provide first order space-time couplings in one direction, but complete spatiotemporal measurement is needed.

Spatiotemporal diagnostics are needed for the whole picture.

- The full spatiotemporal dependencies are written out:

$$E(x,y,z,t) = \mathrm{Re}[\sqrt{I(x,y,z,t)}\ \exp[i(\omega_0 t - \phi(x,y,z,t))]]$$
$$E(x,y,z,\omega) = \sqrt{S(x,y,z,\omega)}\ \exp[-i\varphi(x,y,z,\omega)]$$
$$E(x,y,z,\omega) = \mathscr{F}\{E(x,y,z,t)\}.$$

- To measure these fields, we require a complete spatiotemporal pulse-measurement device.

- Due to low rep rates in high-power systems and laser instabilities, we also require single-shot measurement.

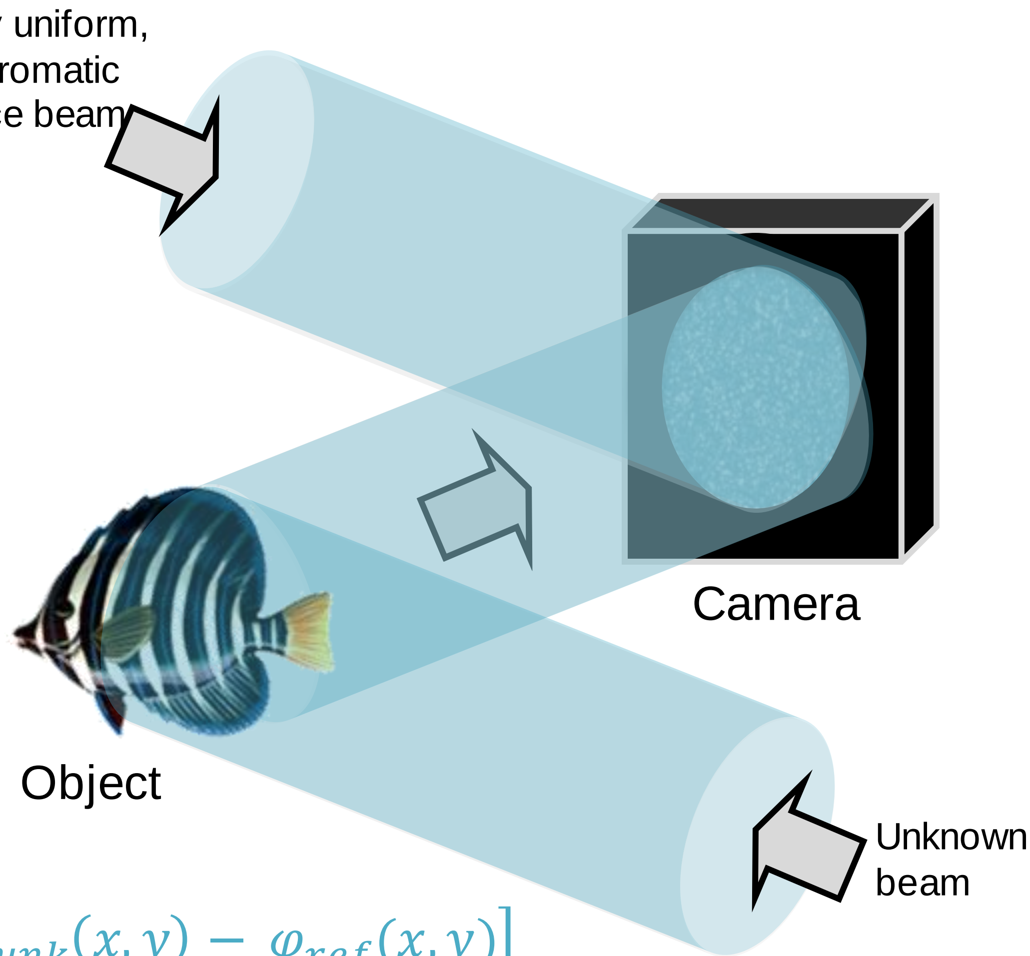
- STRIPED FISH solves this problem by taking single-shot complete spatiotemporal pulse measurements.

Holography for Single-Shot Spatial and Temporal Measurement

Measure the integrated intensity $I(x,y)$ of the sum of known and unknown monochromatic beams.

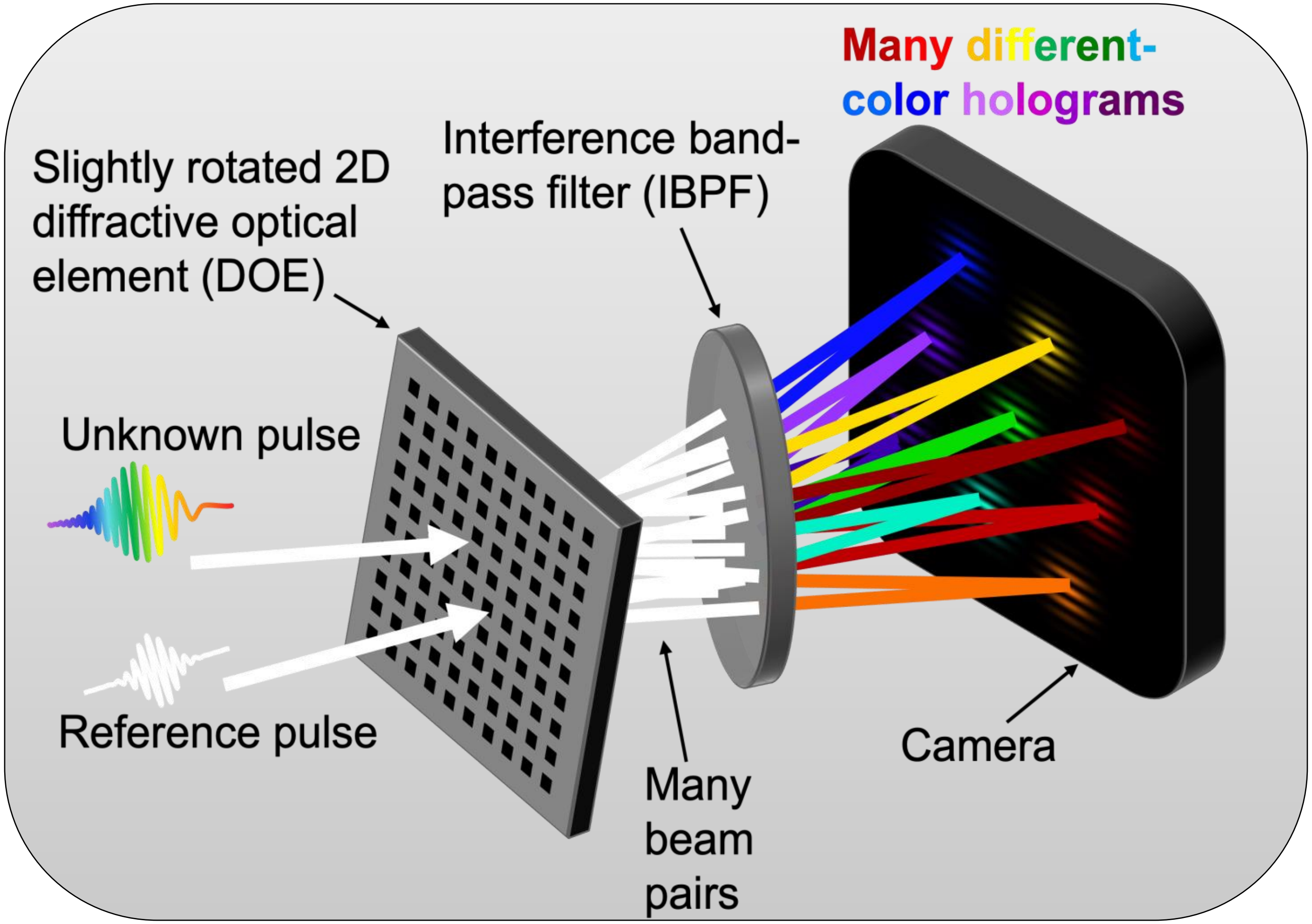
Extract the unknown monochromatic field $E(x,y)$ from the **cross term**.

$$\boldsymbol{I_{holo}(x,y)} = \boldsymbol{I_{ref}(x,y)} + \boldsymbol{I_{unk}(x,y)} + 2\sqrt{\boldsymbol{I_{ref}(x,y)}}\sqrt{\boldsymbol{I_{unk}(x,y)}}\cos[\varphi_{unk}(x,y) - \varphi_{ref}(x,y)]$$



Holography can provide the wavefront of the laser pulse.

Spatially and Temporally Resolved Intensity and Phase Evaluation Device: Full Information from a Single Hologram (STRIPED FISH)



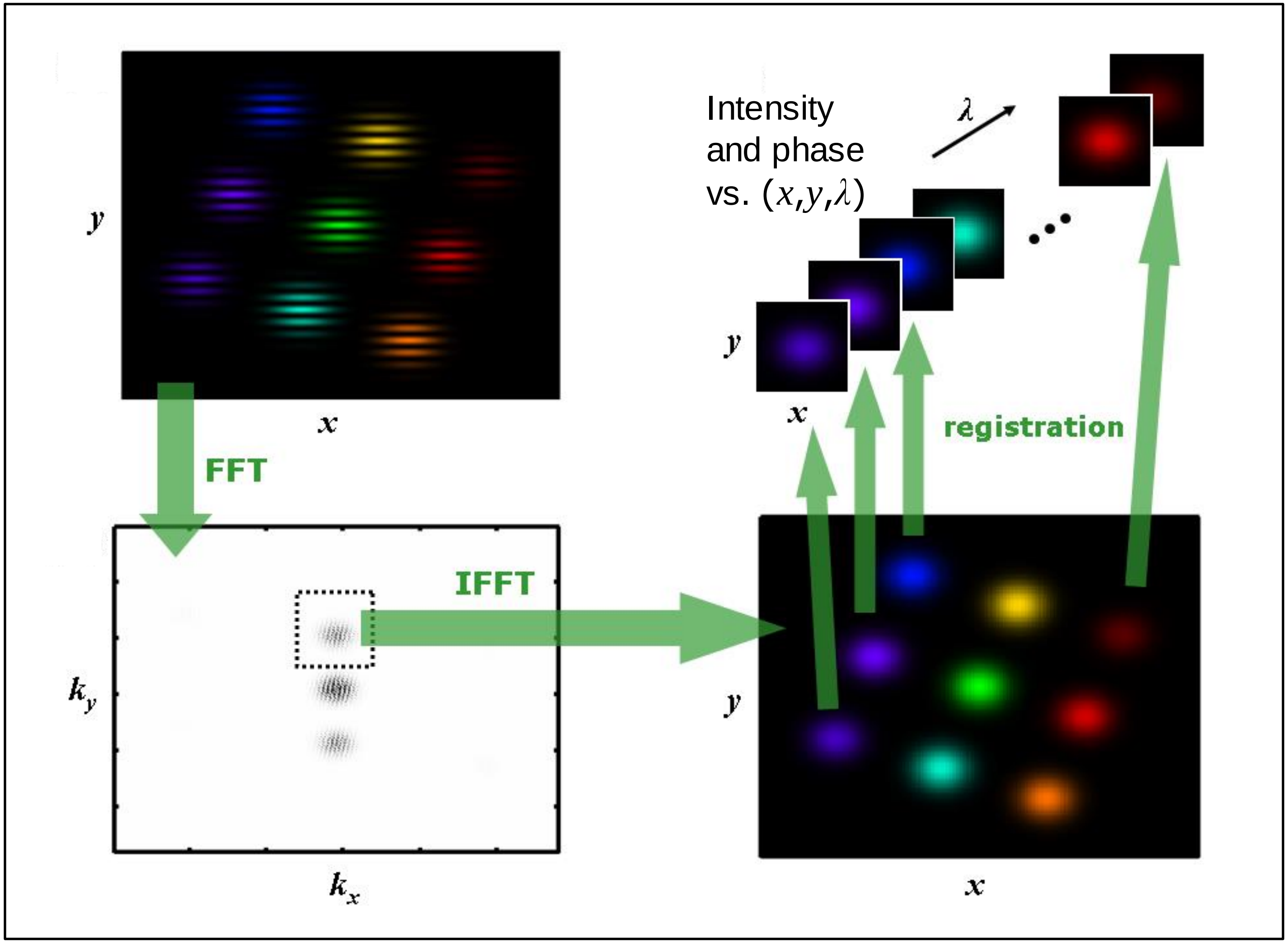
By spectrally resolving the holograms, we obtain the wavefront at each frequency present in the laser pulse.

Gabolde *et al,* JOSAB (2008).

Theoretical STRIPED FISH trace for a simple pulse

False color indicates frequency

The STRIPED FISH retrieval algorithm yields the complete pulse spatio-spectral field.

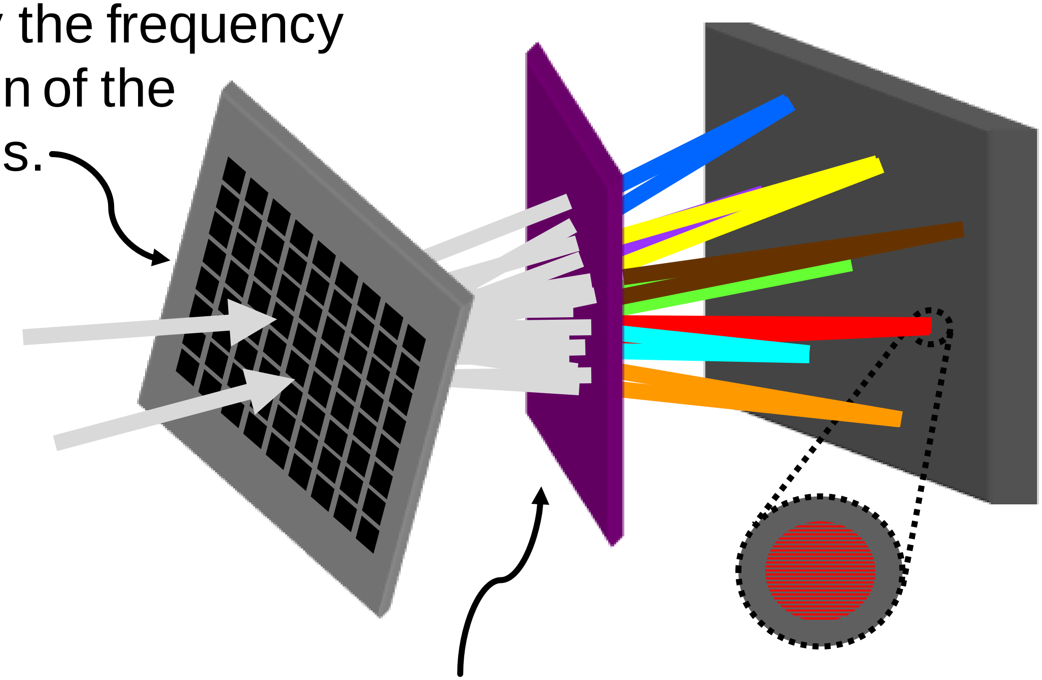


*P. Gabolde and R. Trebino, J. Opt. Soc. Am. B **25** A25 (2008)

STRIPED FISH can measure laser pulses ranging from fs to 10 ps

Temporal resolution is limited by the frequency separation of the holograms.

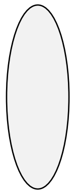
Spatial resolution and range are limited by the camera.

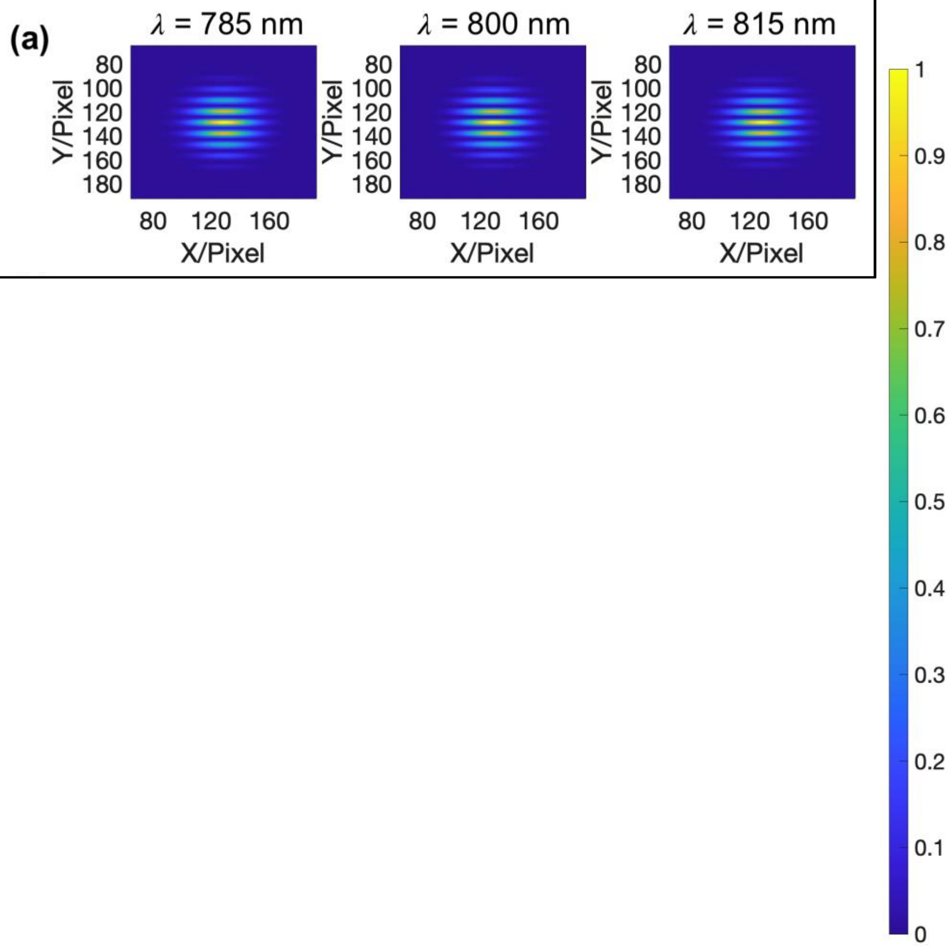


The temporal range is limited by the spectral resolution of the bandpass filter. Temporal range can be significantly increased if multiple delays are used, but no longer single shot.

What can be seen directly from the STRIPED FISH trace?

Undistorted pulse

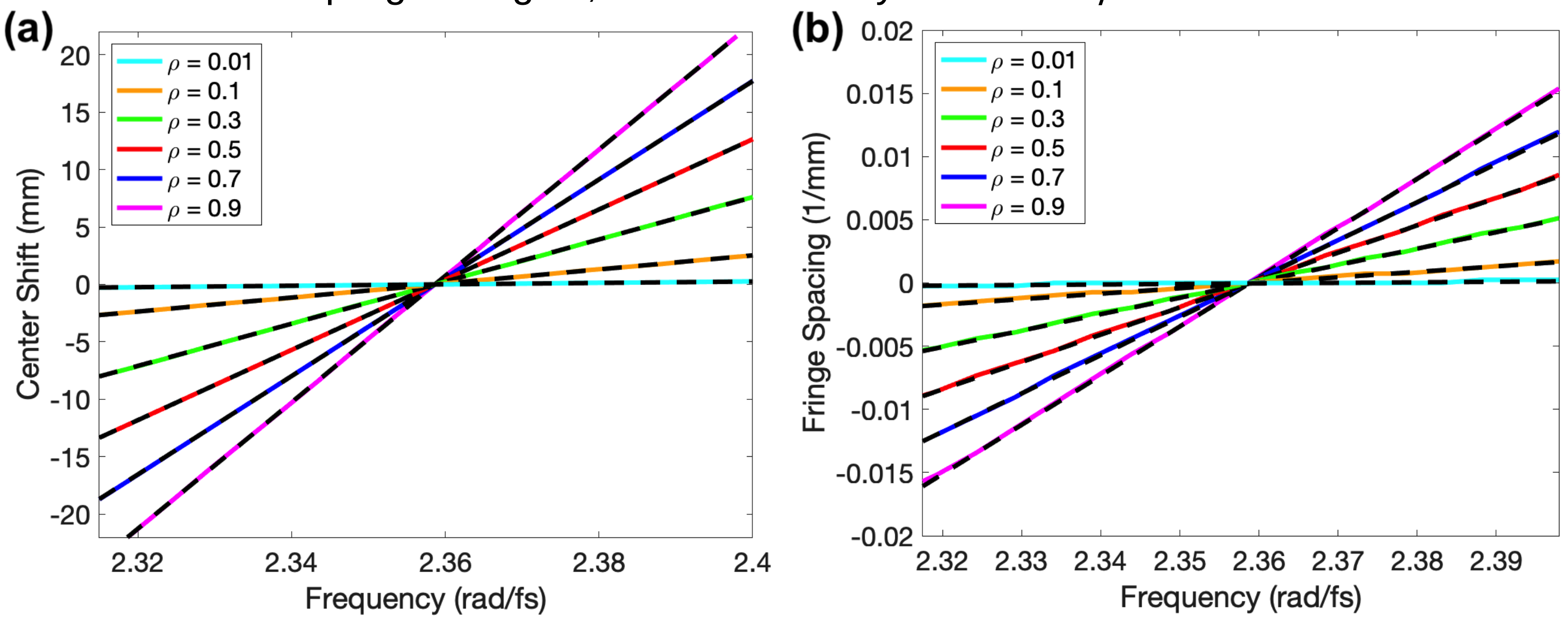




*E. Grace *et al.*, *“Rapid retrieval of first-order spatiotemporal distortions for ultrashort laser pulses,”* Plas. Phys. Control. Fus. **63**(12): 124005 (2021)

Reading these changes directly from the trace also results in a rapid algorithm for high repetition rate feedback.

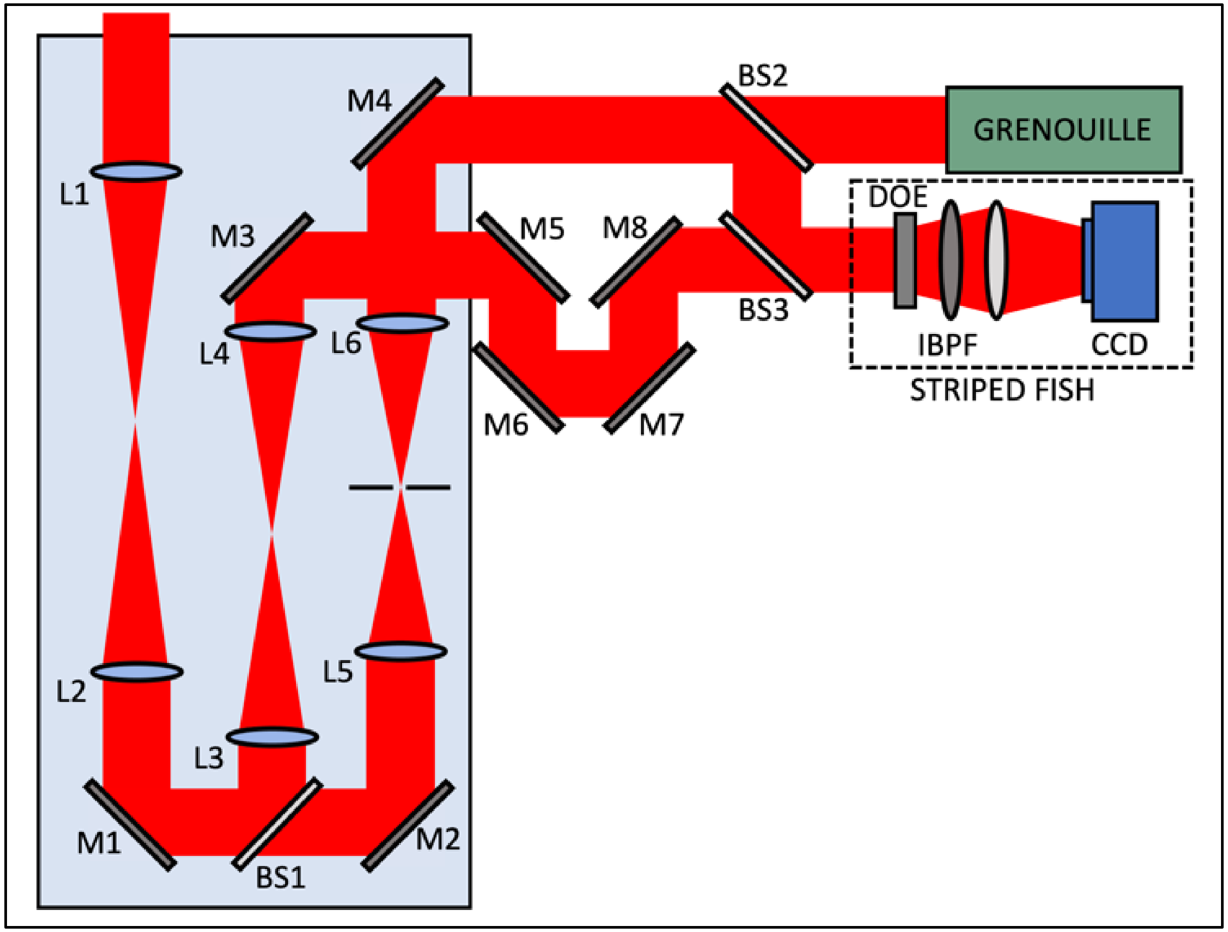
These plots show the retrieval performance for different coupling strengths, as described by the scalar ρ.



Due to the interrelation of spatiotemporal couplings, for collimated beams, the rest of the first-order spatiotemporal couplings can be calculated from these values.

The retrieval algorithm rapidly provides the same first-order information as the complex 4-D retrieval provides with <1% error even for highly distorted pulses.

The first on-shot full-power spatiotemporal measurement was taken at the Jupiter Laser Facility's COMET laser. 28 shots were taken over one day.



COMET: Compact Multipulse Terawatt

Repetition rate: 15 shots / hour

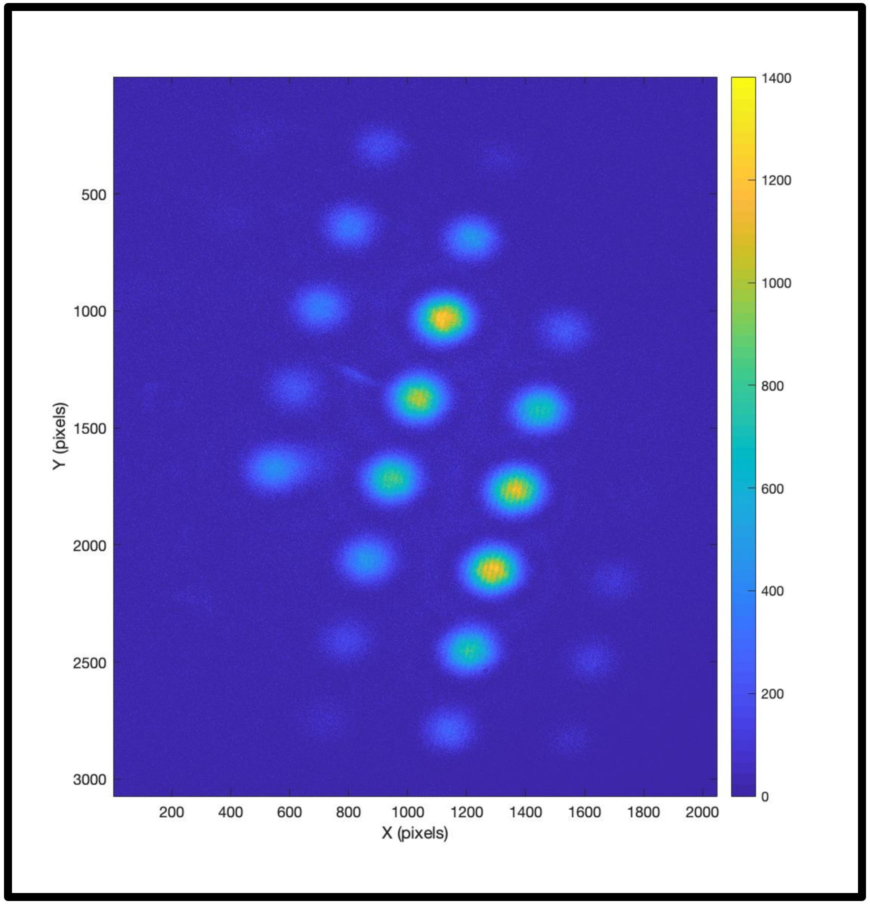
Max energy on target: ~10 J

Short pulse length: 1ps

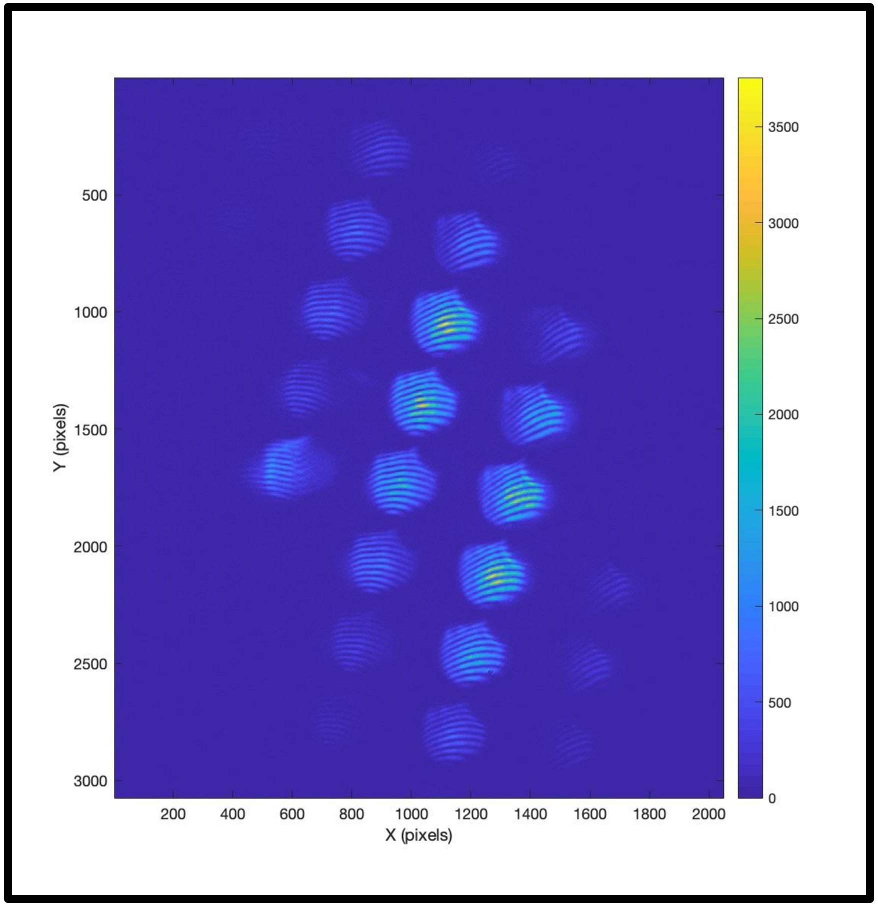
*E. Grace *et al.*, "*Single-Shot Complete Spatiotemporal Measurement of Terawatt Laser Pulses,*" J. Opt. (2021).

Raw single-pulse data of COMET short pulse at max available intensity (0.3J – during maintenance phase)

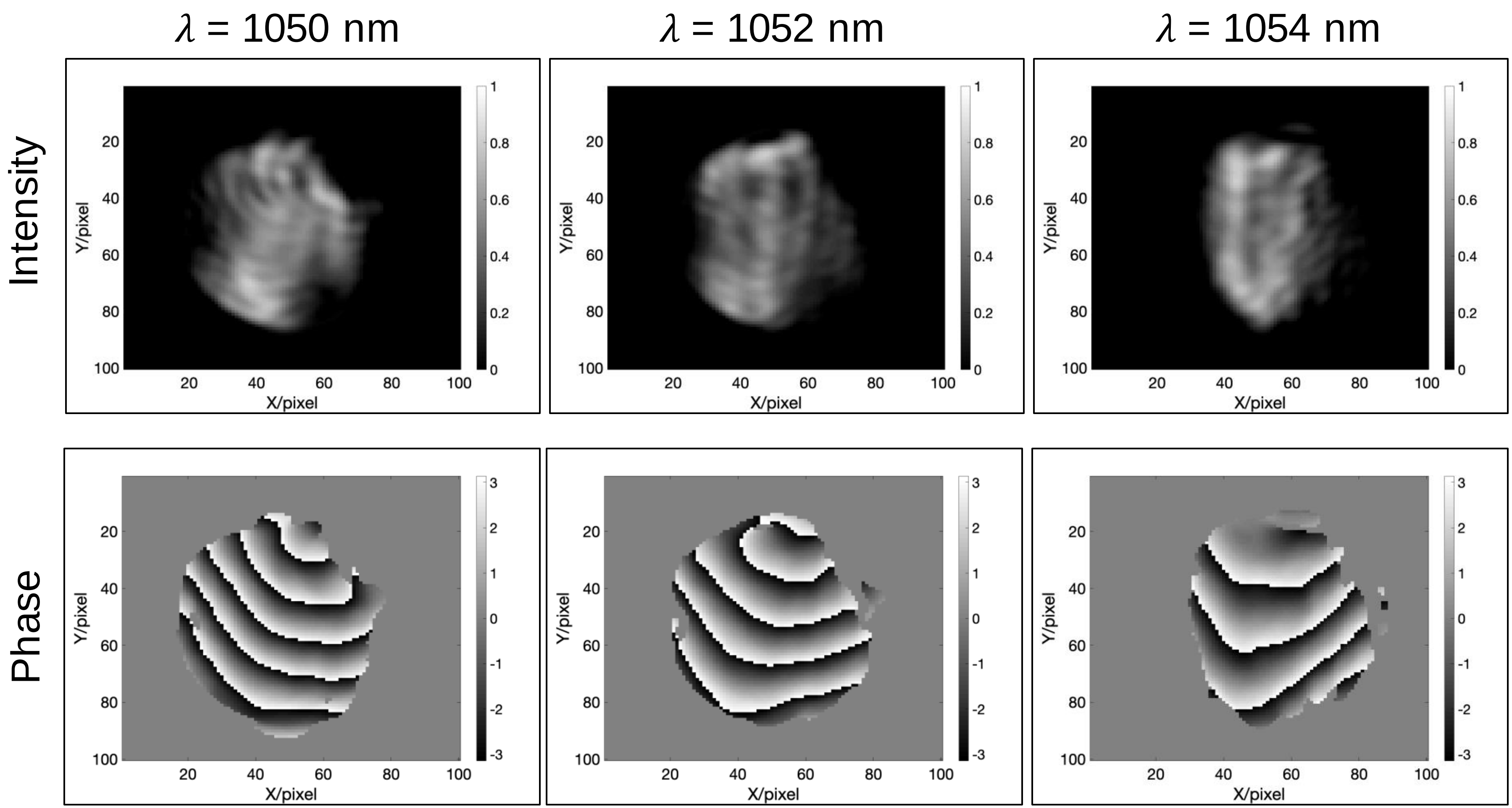
Calibration (reference) trace



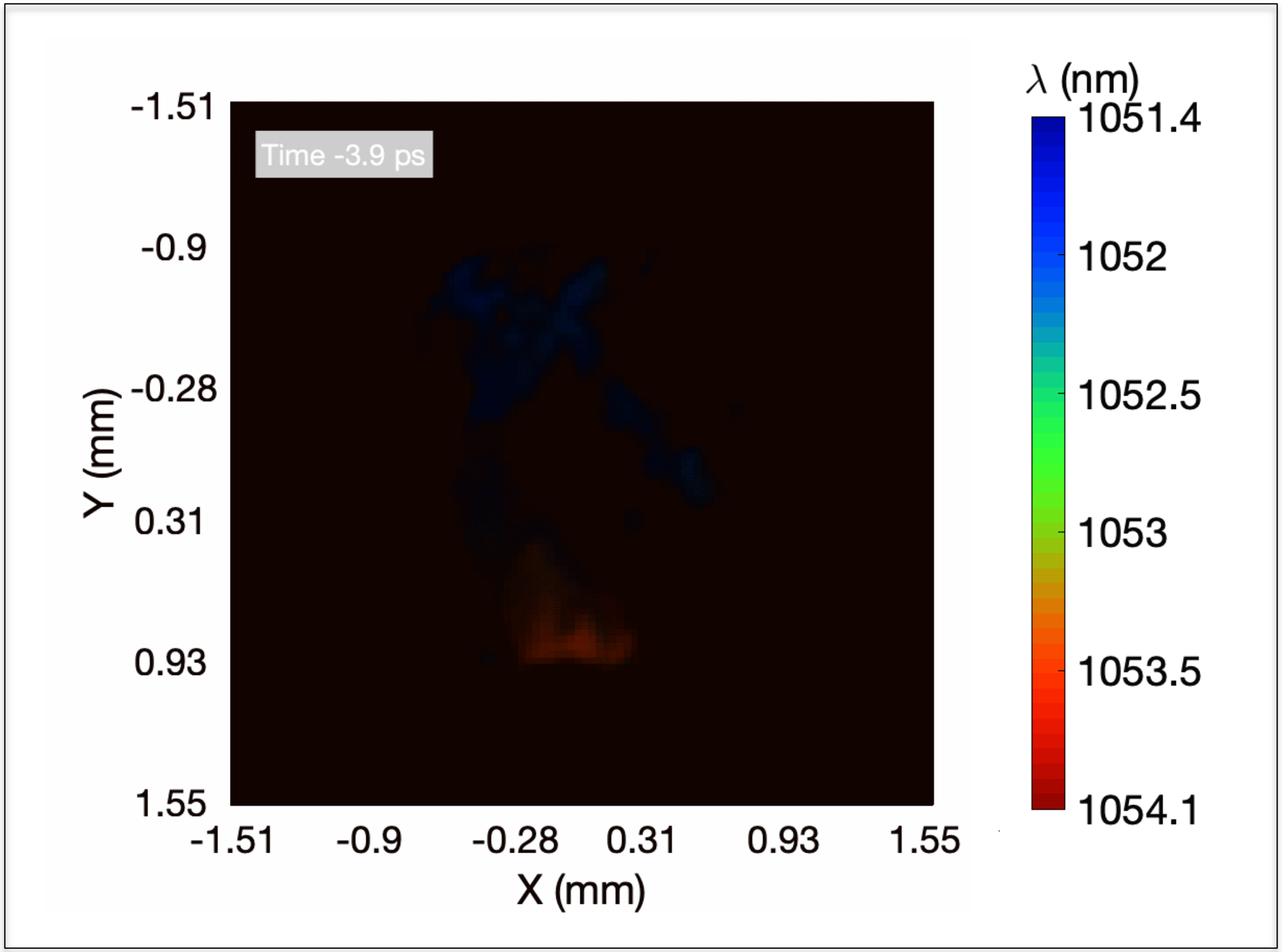
Data Taken On-Shot



STRIPED FISH provides the spatial-spectral intensity and phase (and does so directly).

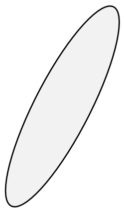


The retrieved movie shows spatiotemporal complexity.

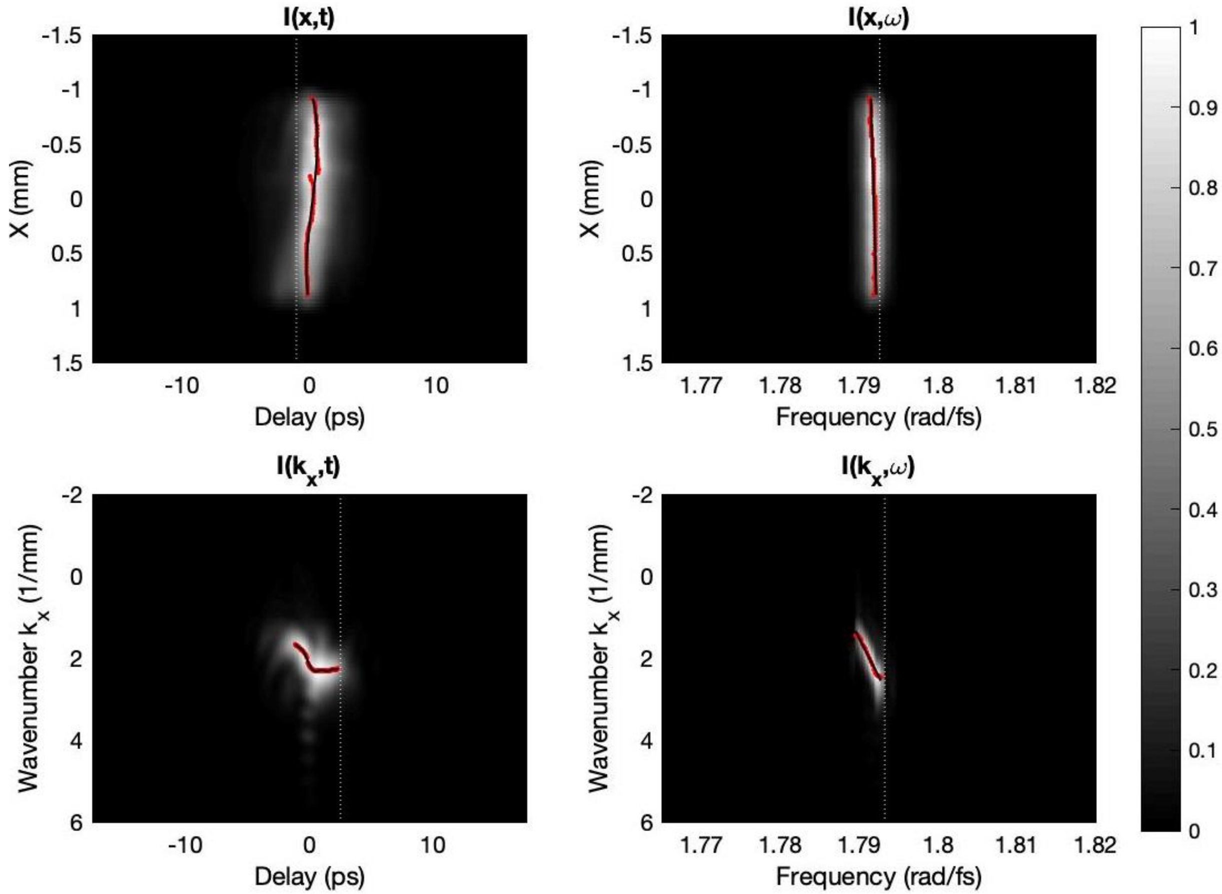


Trends in COMET's spatiotemporal couplings across all 28 shots emerged.

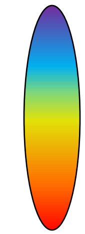
(x,t): Pulse front tilt



(kx,t): Ultrafast lighthouse



(x,ω): Spatial chirp

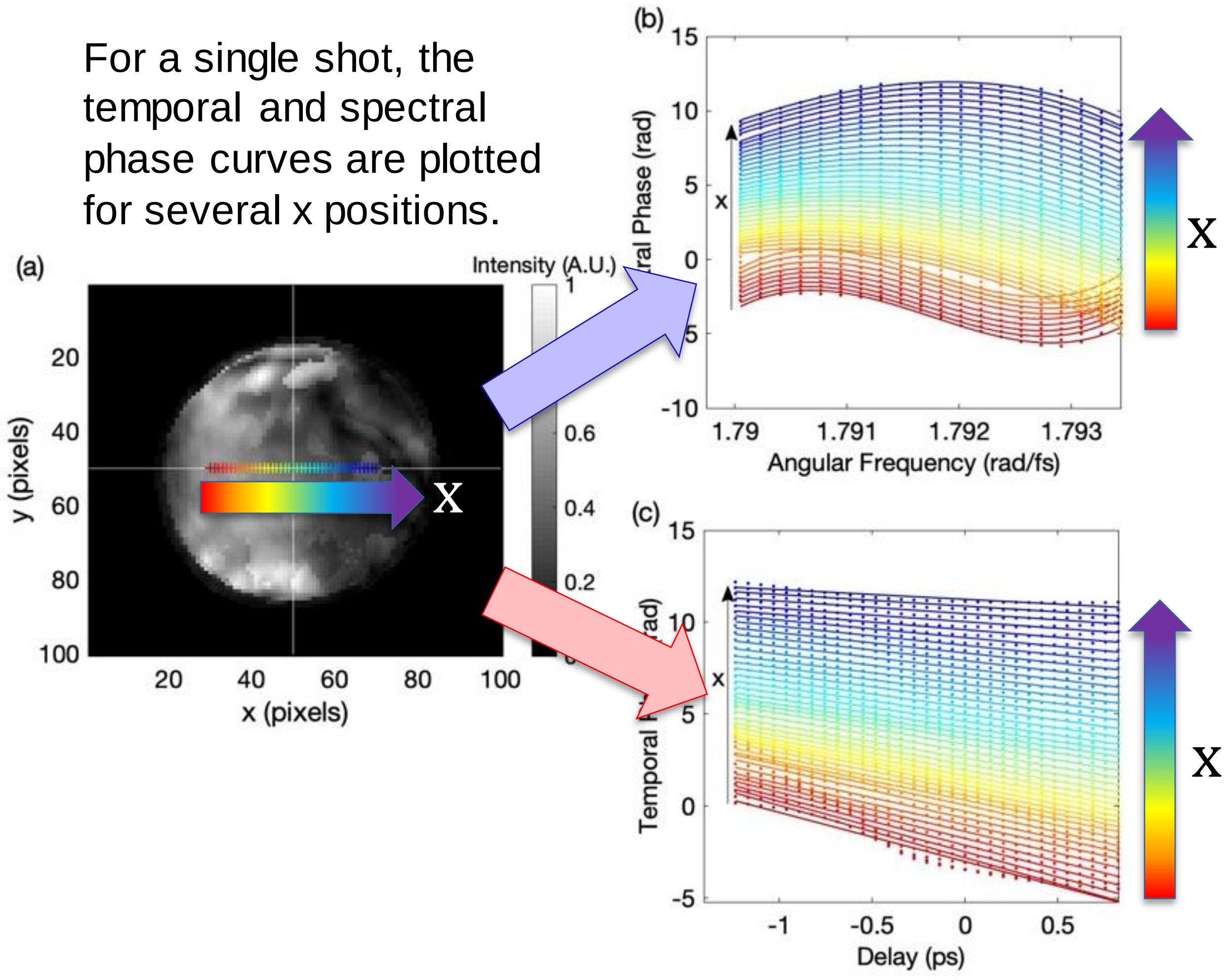


(k_x,ω): Angular dispersion

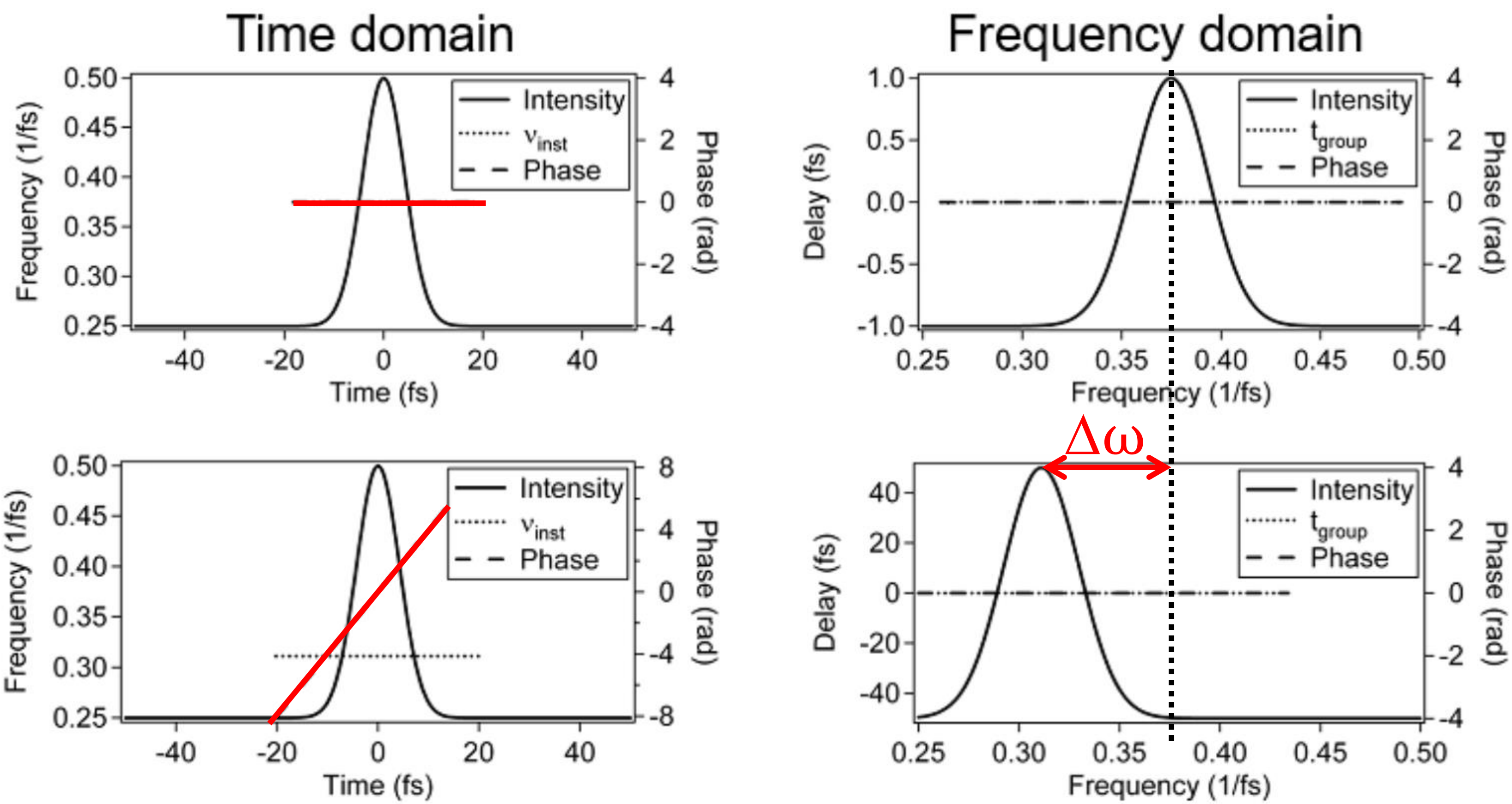
The shear (red line) was extracted from these plots and fit to a polynomial, separating the first-order and higher-order contributions to the coupling.

The temporal and spectral phase plots vs. x provide the arrival time delay and frequency gradient.

For a single shot, the temporal and spectral phase curves are plotted for several x positions.



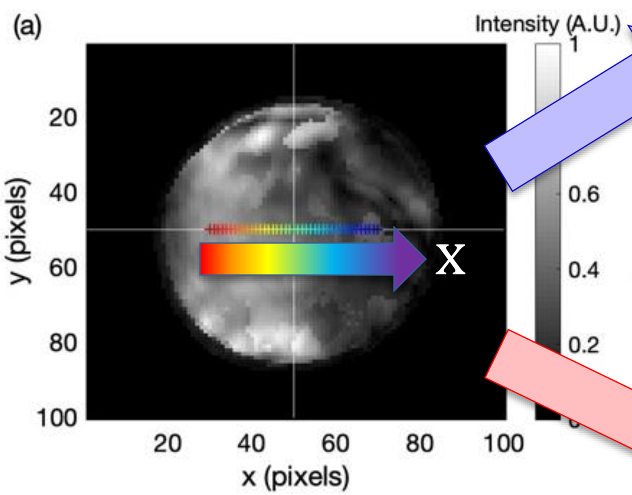
Keep in mind: a linear spectral phase is a delay in time. Similarly, a linear temporal phase is a frequency shift.

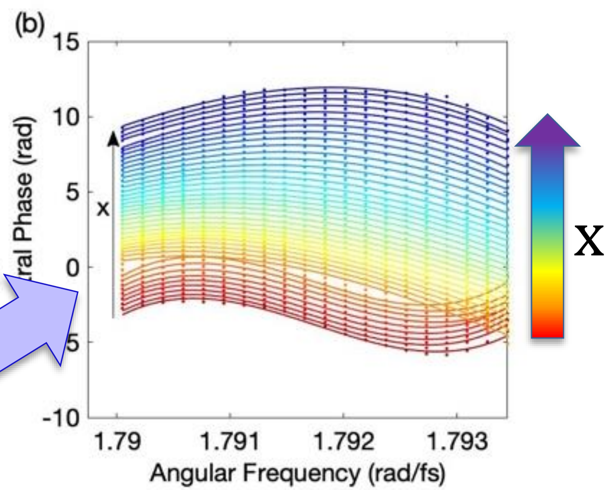


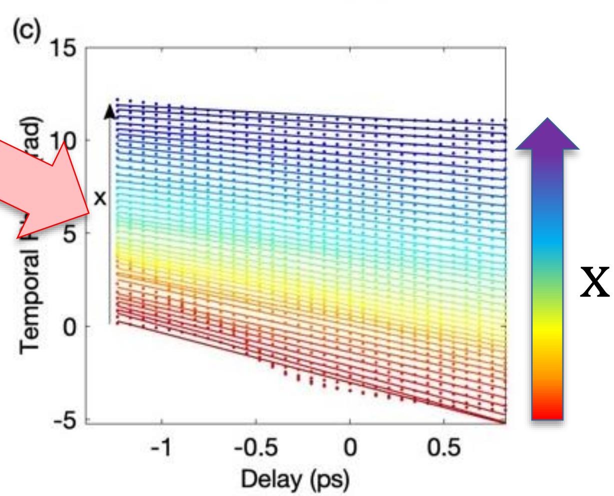
So, a change in slope of the linear temporal phase across x indicates that the center frequency is moving across x.

From this relationship, the temporal and spectral phase plots vs. x provide the arrival time delay and frequency gradient.

For a single shot, the temporal and spectral phase curves are plotted for several x positions.



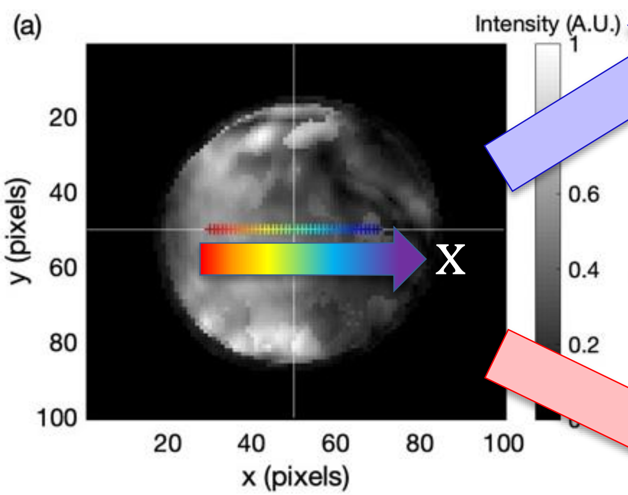


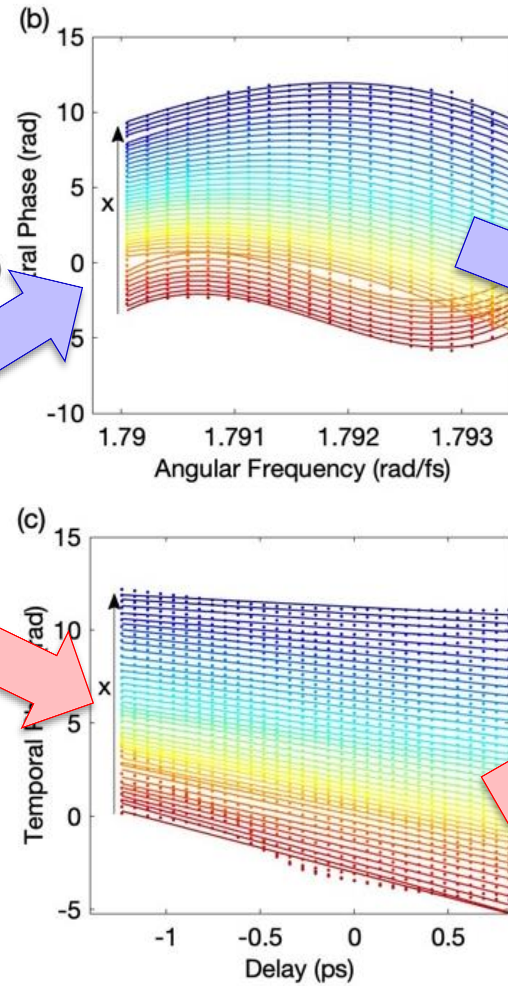


So, a change in slope of the linear phase across x means that the center frequency is moving across x.

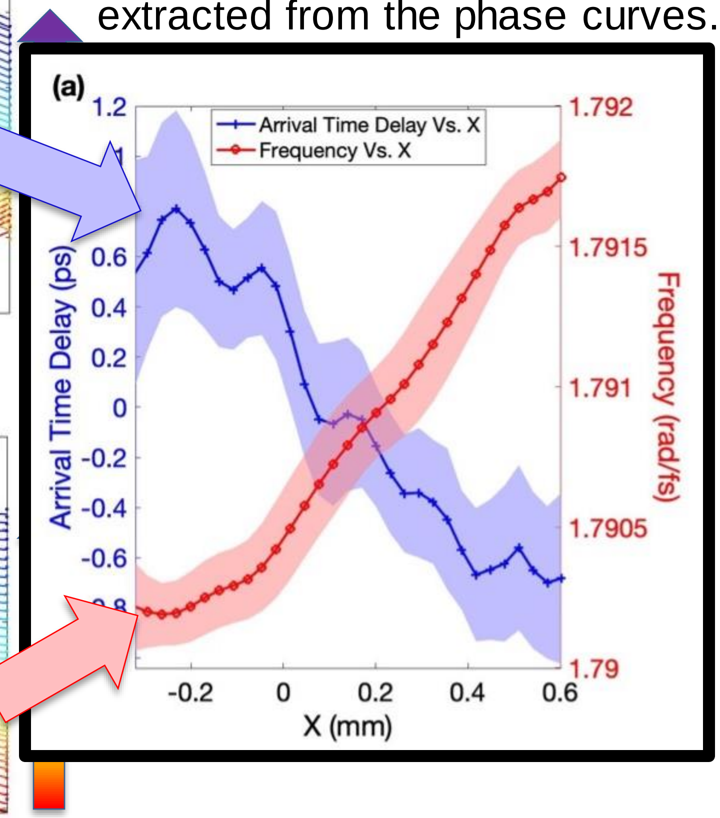
From this relationship, the temporal and spectral phase plots vs. x provide the arrival time delay and frequency gradient.

For a single shot, the temporal and spectral phase curves are plotted for several x positions.





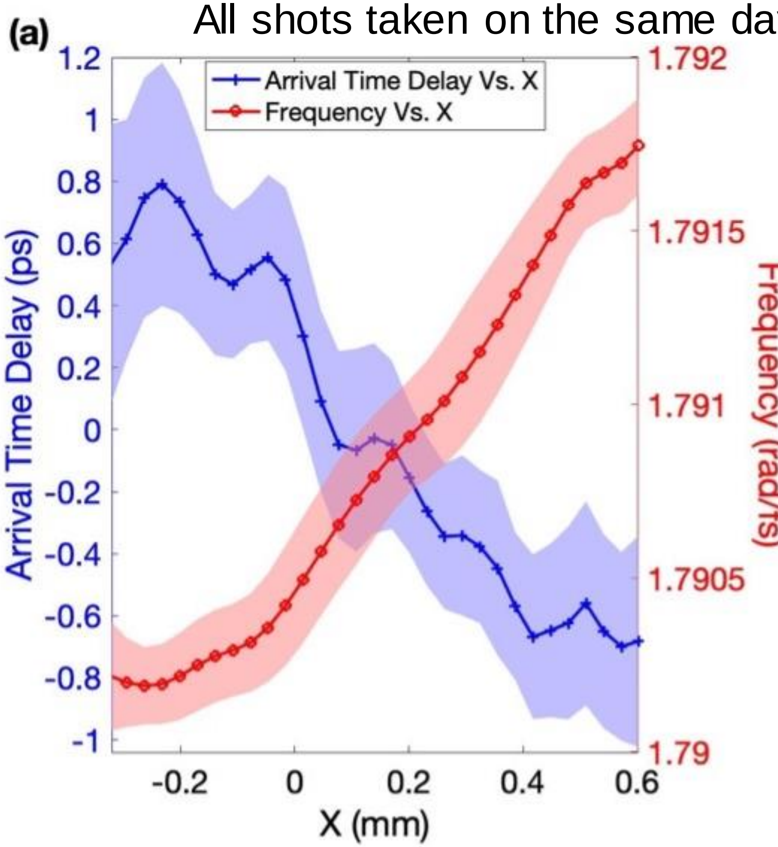
For all shots, the arrival time delay and frequency gradient are extracted from the phase curves.

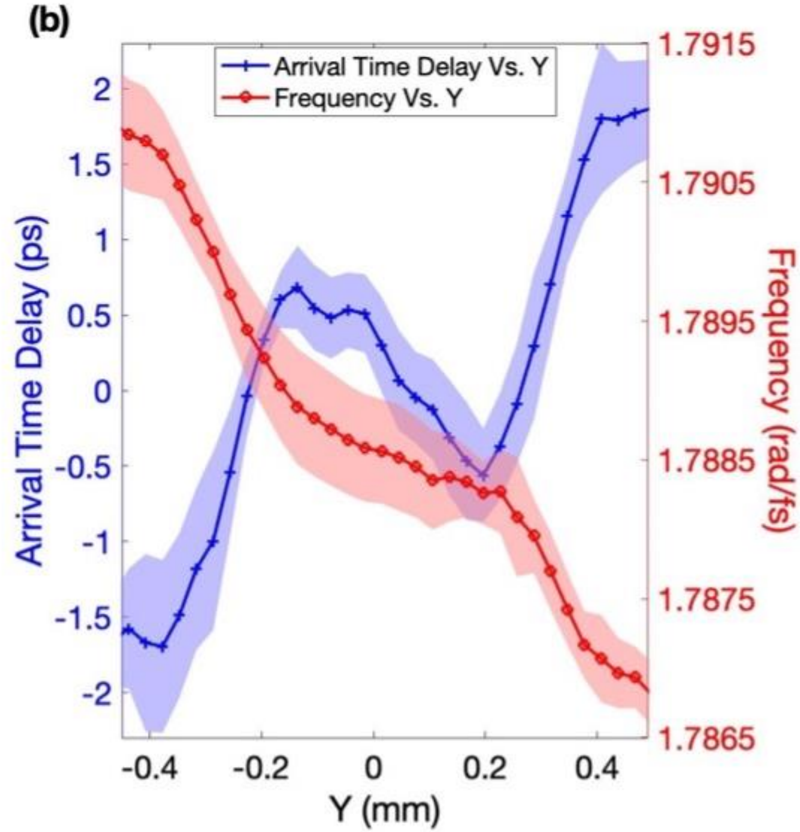


So, a change in slope of the linear phase across x means that the center frequency is moving across x.

Arrival time delay and frequency vs. space are extracted from the phase plots for both transverse dimensions.

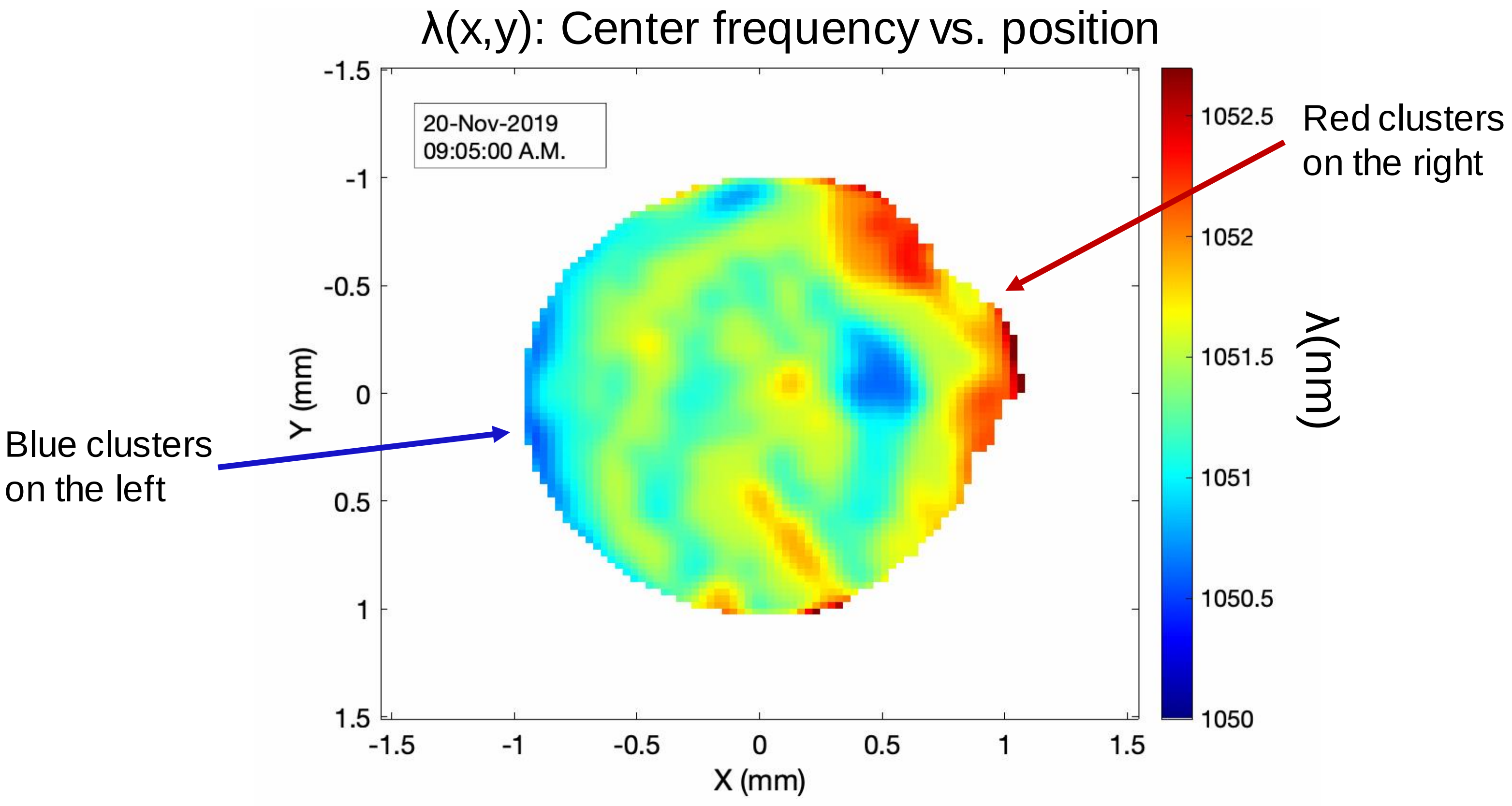
Error envelope indicates the shot-to-shot fluctuation in that value.
All shots taken on the same day.





The phase curves provide these plots for pulse front tilt and spatial chirp for all shots, which corroborate the shear plots.

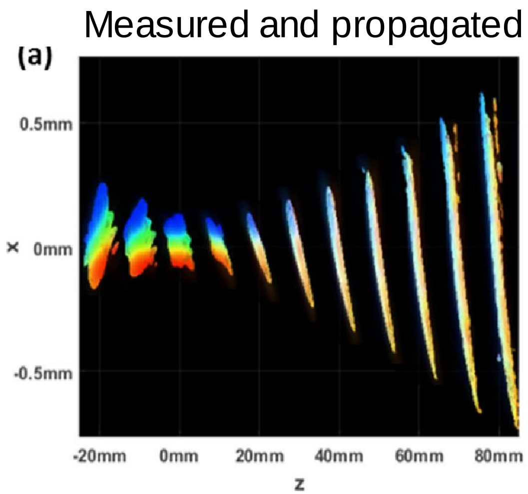
These distortions varied shot-to-shot.

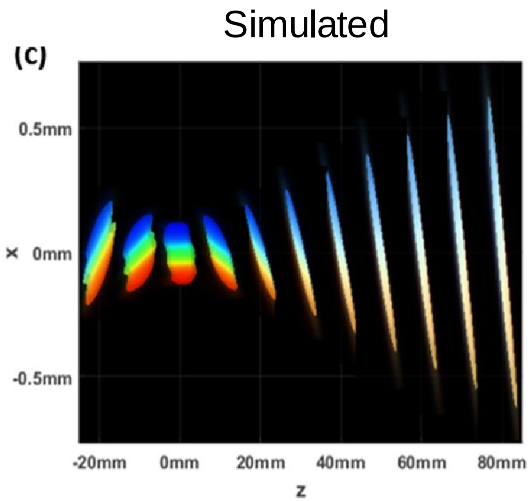


Shot-to-shot variations cannot be captured by multi-shot methods, which must assume shot-to-shot stability. STRIPED FISH uniquely provides this measurement.

So far, we have seen the field at the STRIPED FISH measurement plane. But what about the focus?

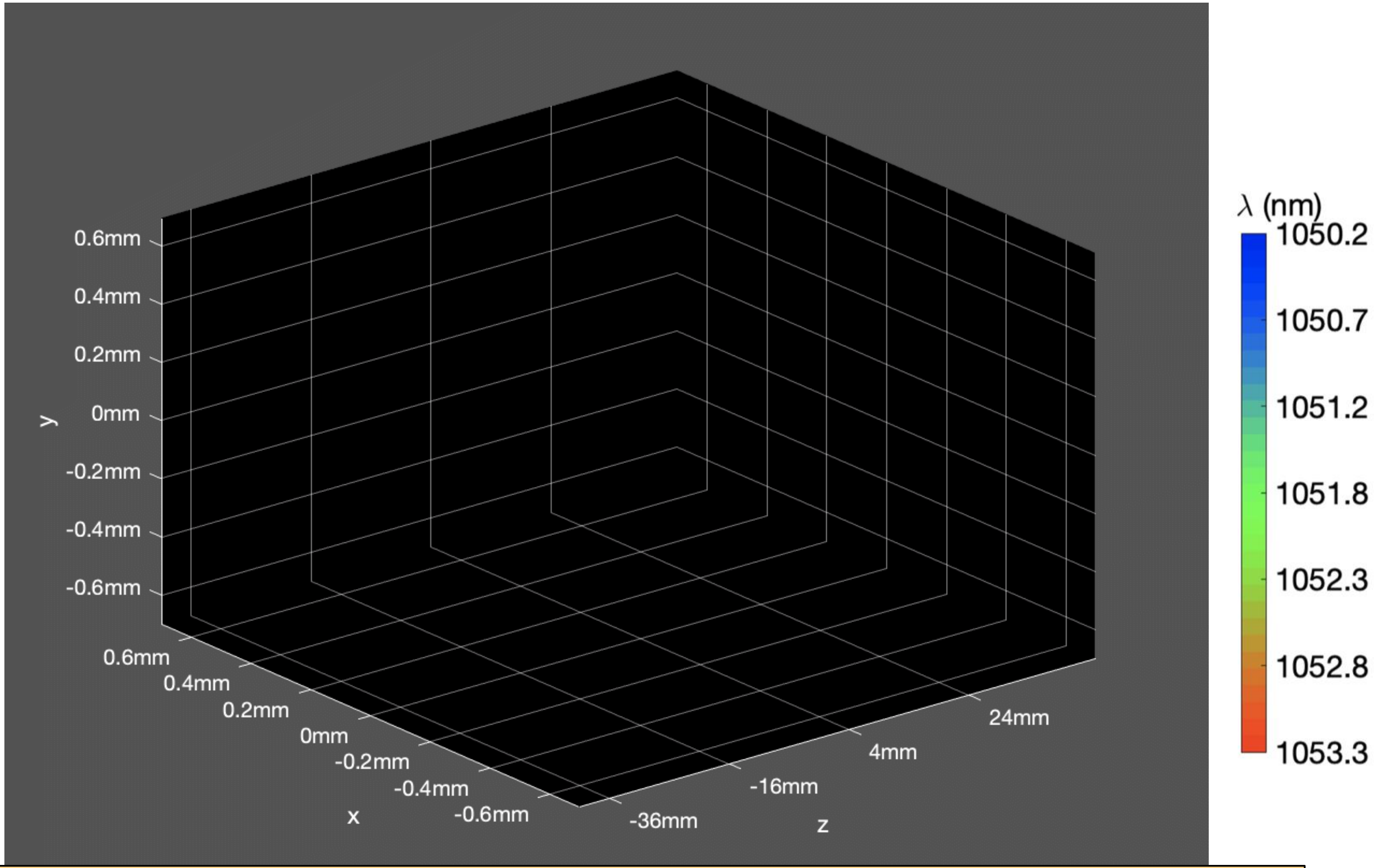
- Because STRIPED FISH provides such complete information about the pulse, the measurement can be used to obtain the complete electric field at the focus as well.
- STRIPED FISH uniquely provides the complete information *E(x,y,t)* required to propagate the pulse in the *z*-direction.
- Angular-spectrum diffraction integrals are used to propagate the pulse.





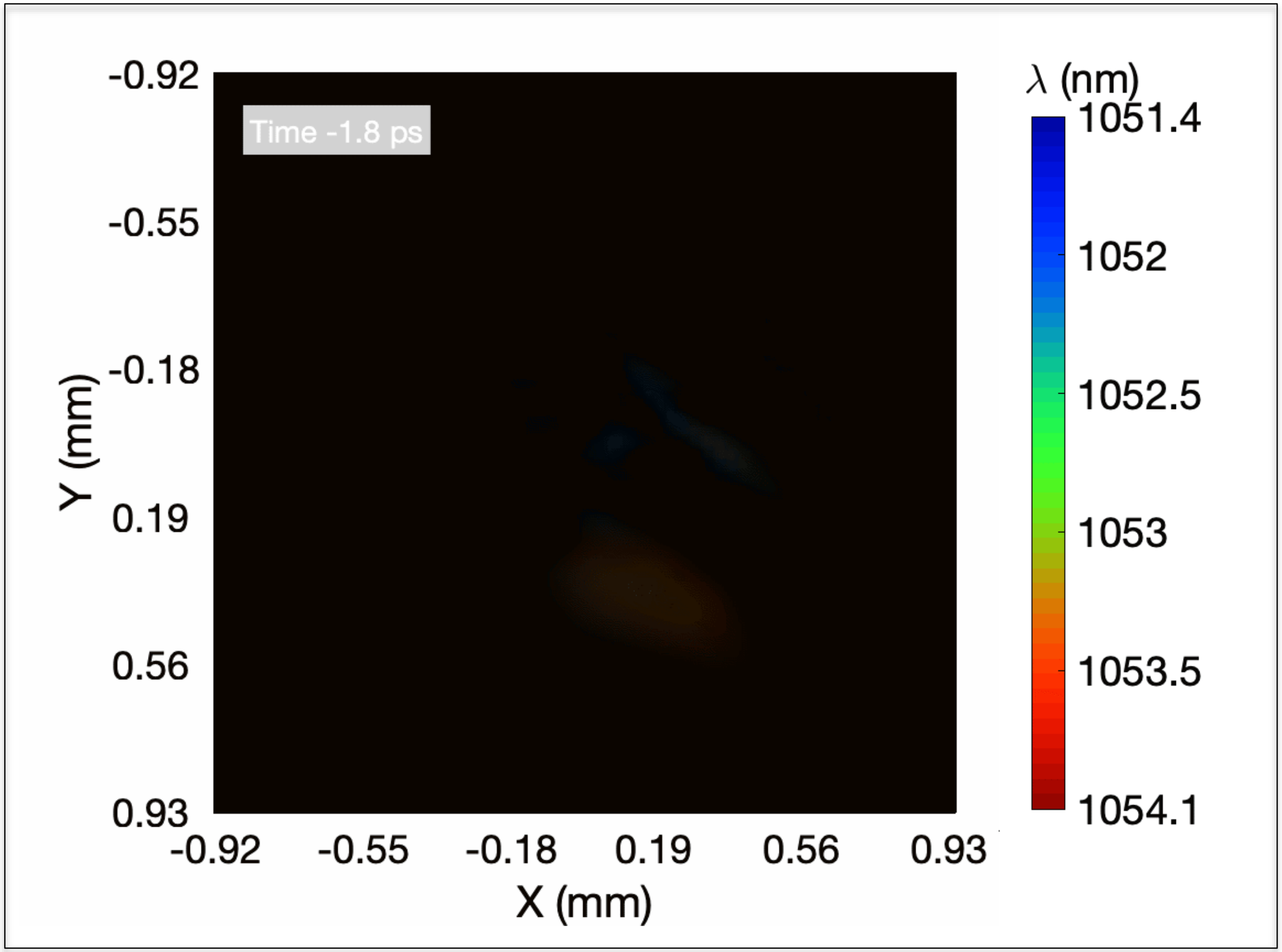
STRIPED FISH can also be used to obtain the electric field at the focus.

Angular-spectrum diffraction integrals propagate the electric field to the focus.



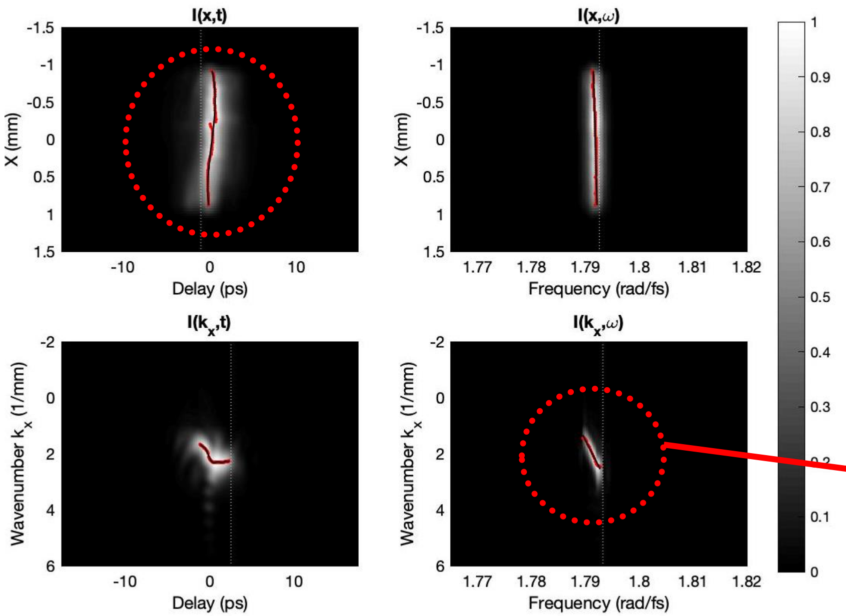
From the movie at the measurement plane, we can extrapolate to any z-location.

The electric field at any point in the z-direction can then be extracted and plotted.

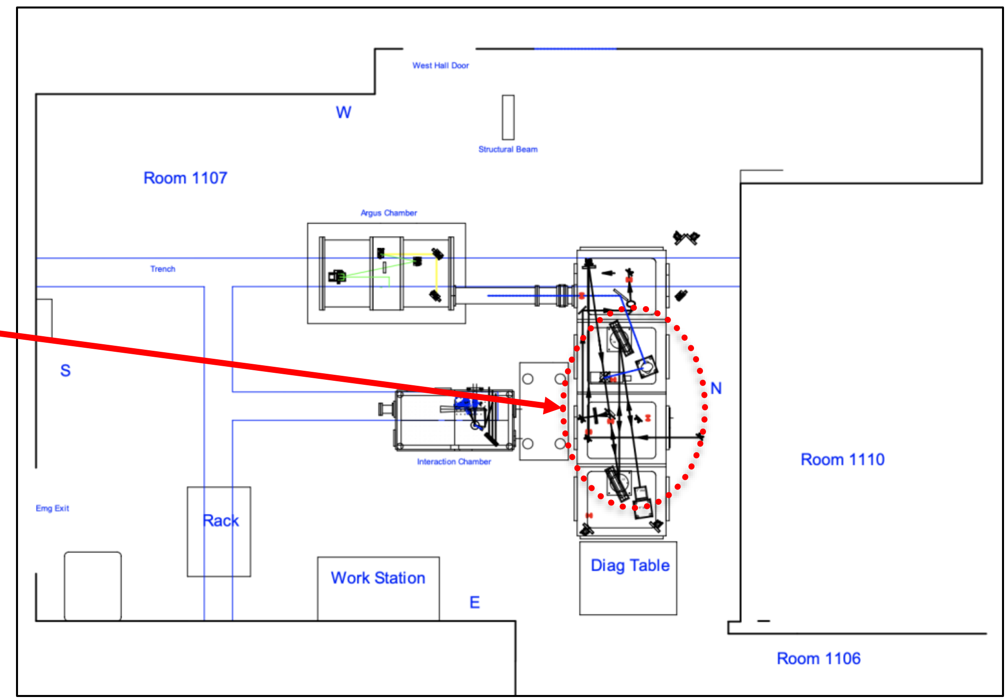


Since the laser electric field is what creates and drives the plasma, the field at the focus can be used as input for simulation codes.

Based on these measurements, we worked with JLF staff to correct the linear effects.

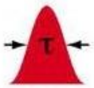


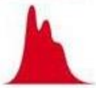
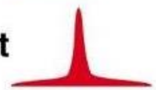
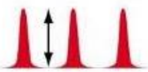
We tracked down the misalignment to the diffraction grating in the compressor and corrected the first-order alignment.

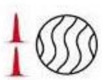
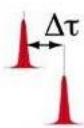


The NIF's Advanced Radiographic Capability (ARC) laser already boasts an impressive set of laser diagnostics.

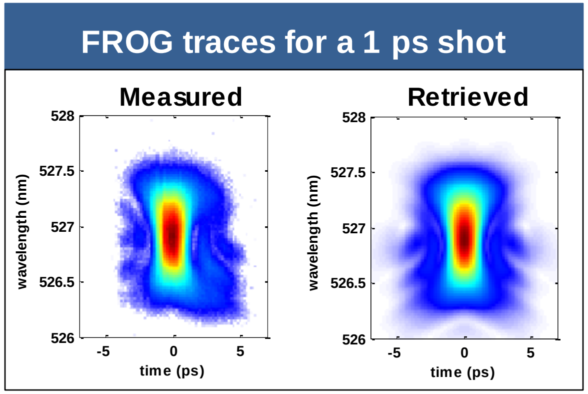
Existing diagnostics on ARC

- **Pulse width** 

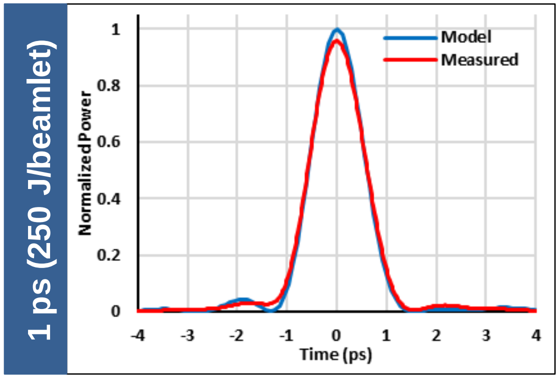
- **Pulse shape** 
- **Pulse contrast** 
- **Pulse energy** 
- **Pulse spectrum** 

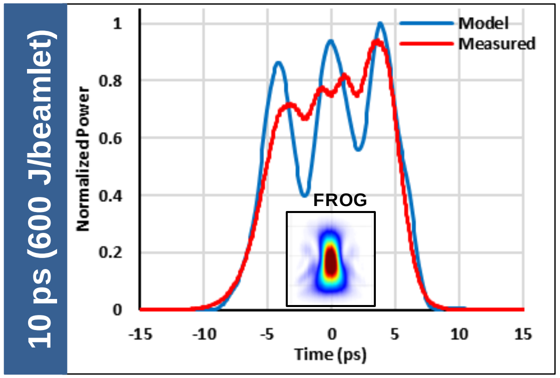
- **Wavefront** 
- **Inter beam coherence** 
- **Relative pulse delay** 

- **Near field** 
- **Far field** 



ARC is already equipped with FROG, which provides the spectral phase for STRIPED FISH.

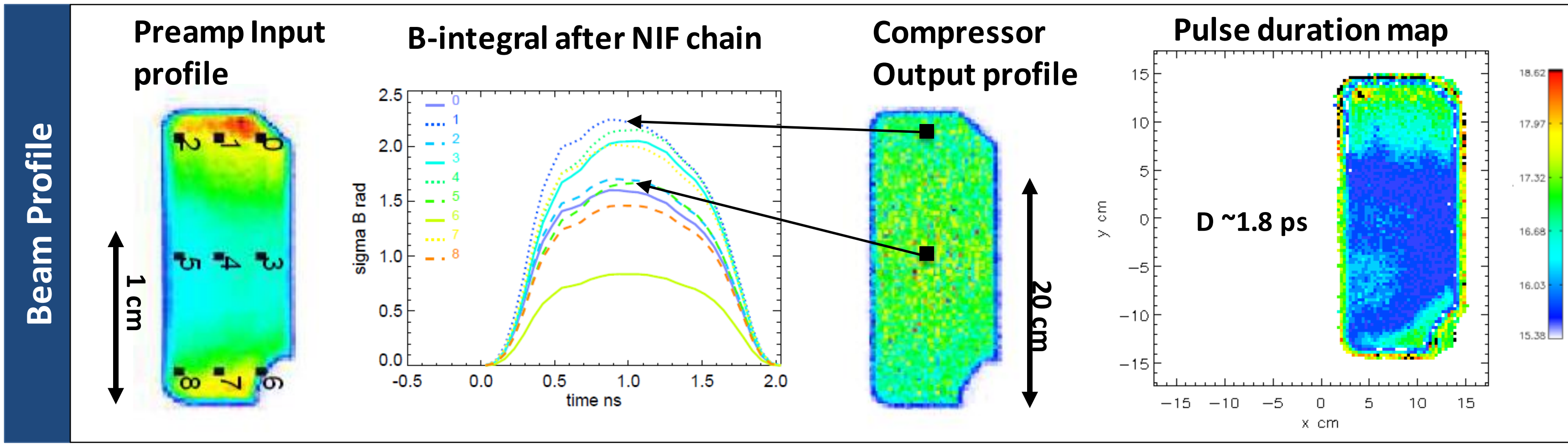


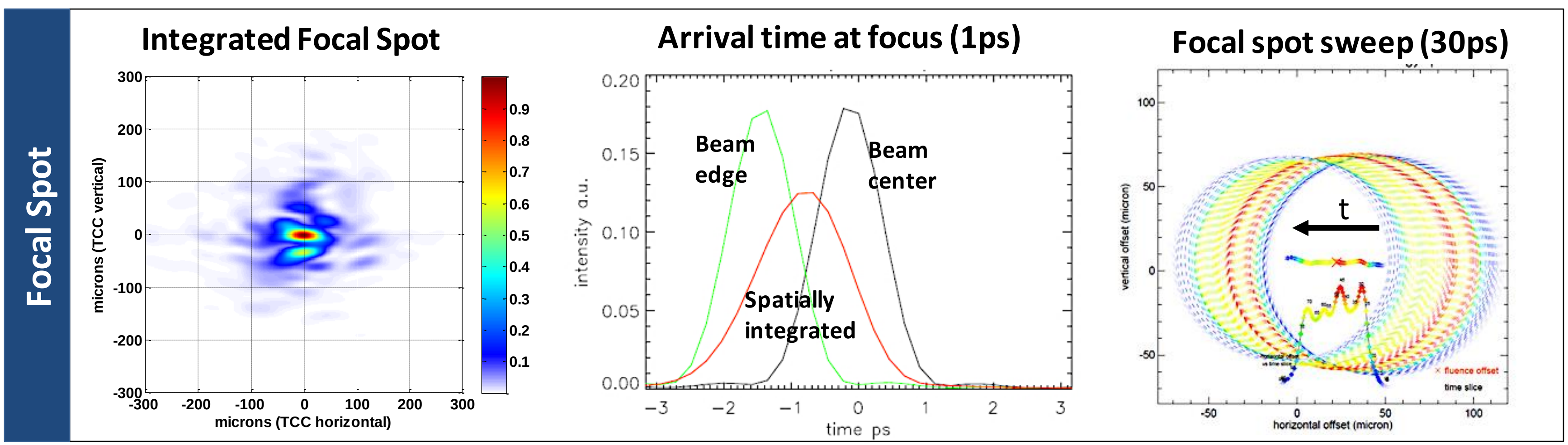


However, ARC is still missing a direct spatiotemporal wavefront measurement.

*ARC team, 2019

ARC currently uses Virtual Beam Line (VBL) to model known spatiotemporal distortions of the laser.

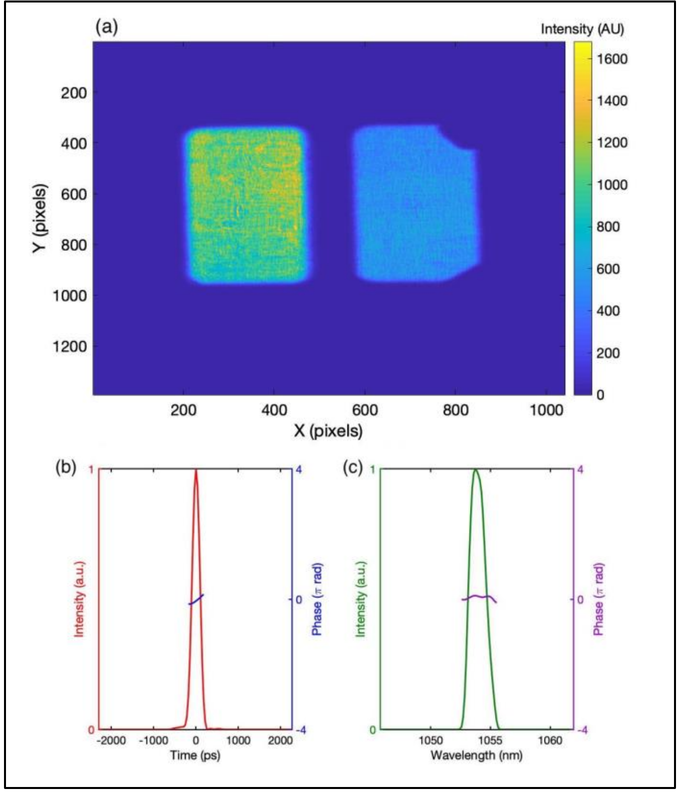




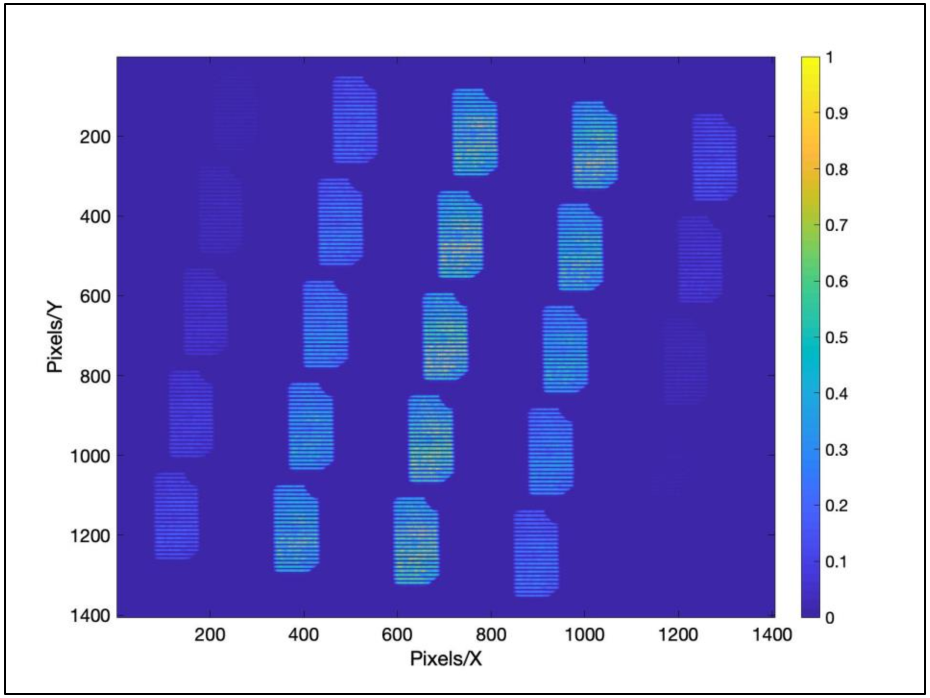
*ARC team, 2019

STRIPED FISH could be applied to directly spatiotemporally characterize ARC with high resolution and validate VBL.

Currently at NIF-ARC, the spatial and temporal measurements are taken separately.

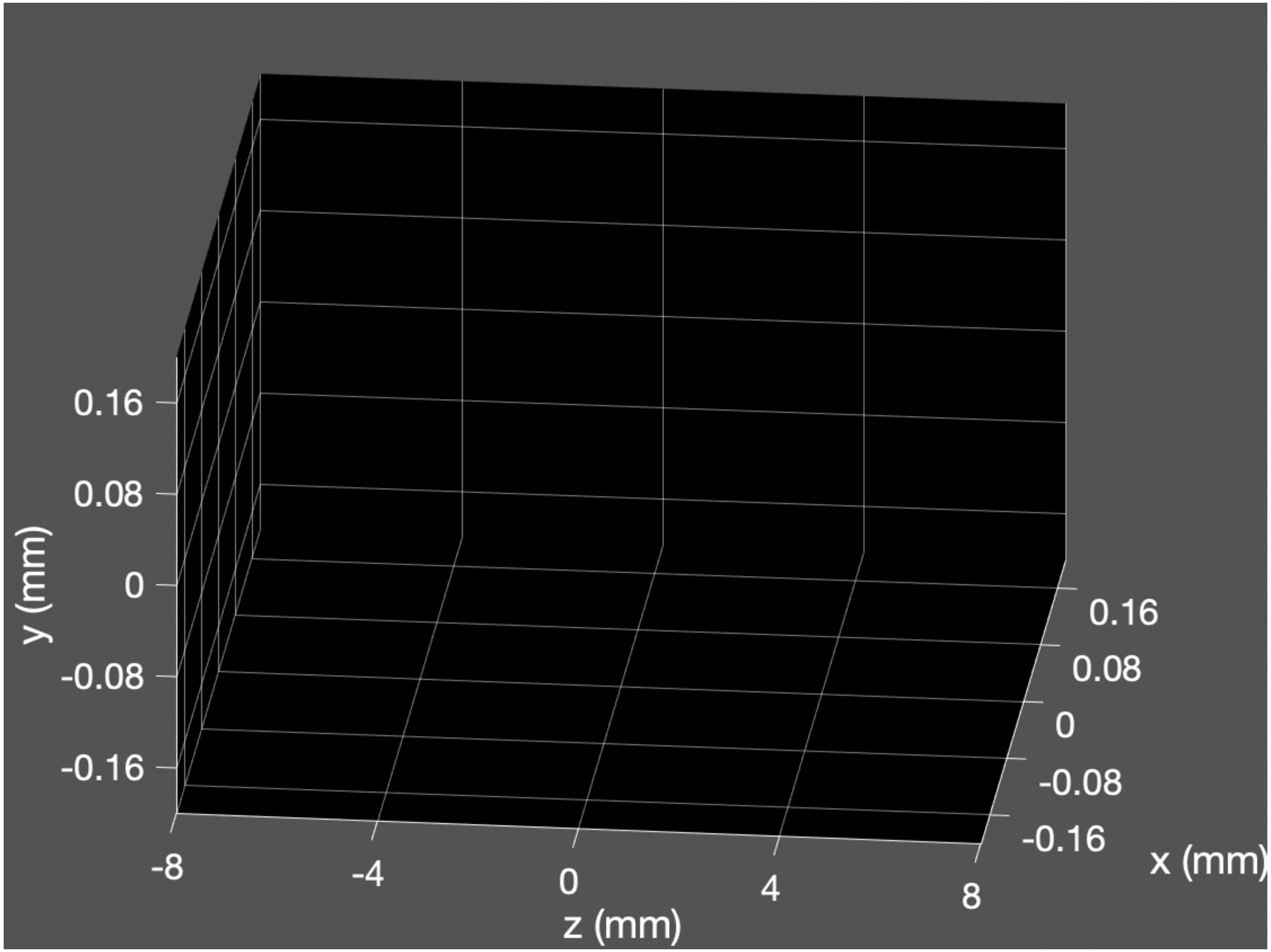


However, NIF-ARC's pulse could be spatiotemporally characterized by STRIPED FISH (simulated trace below).

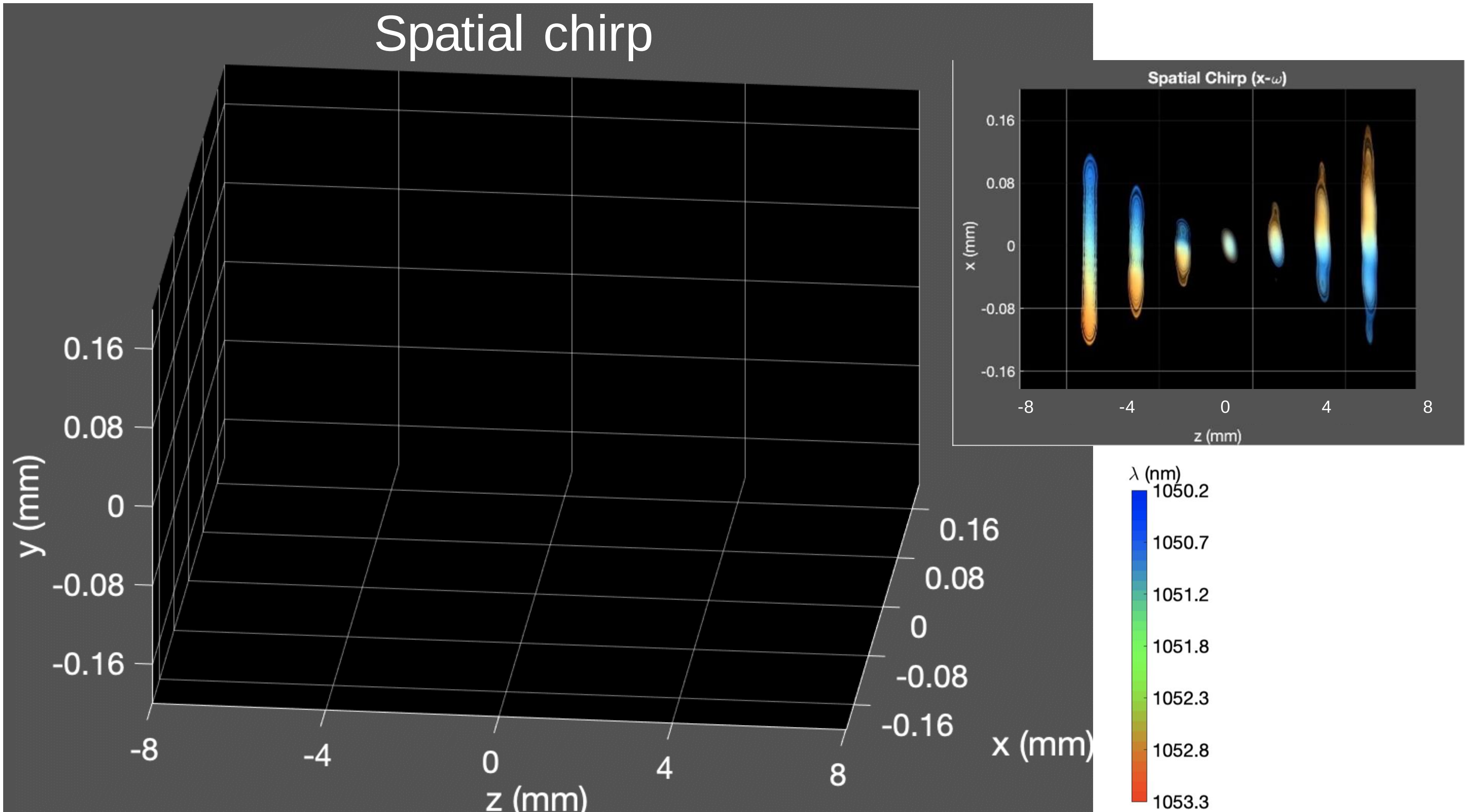


*E. Grace *et al.*, "*Simulations of Wavelength-Multiplexed Holography for Single-Shot Spatiotemporal Characterization of NIF's Advanced Radiographic Capability (ARC) Laser,"* Rev. Sci. Instr. **92**(5):053003 (2021).

It is possible that the ARC field is spatiotemporally uncoupled and we have E(x,y,t) = E(x,y)E(t)…

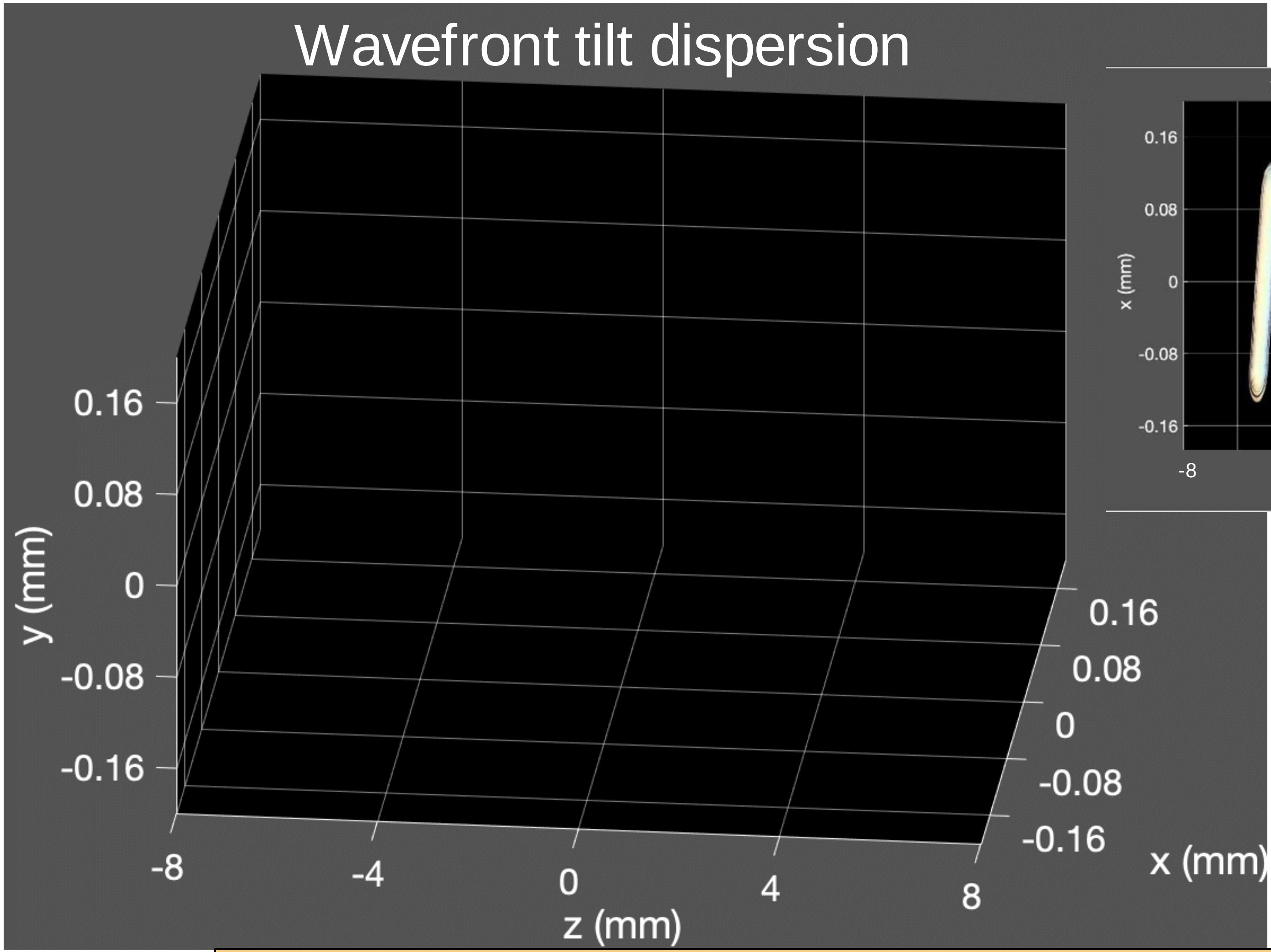


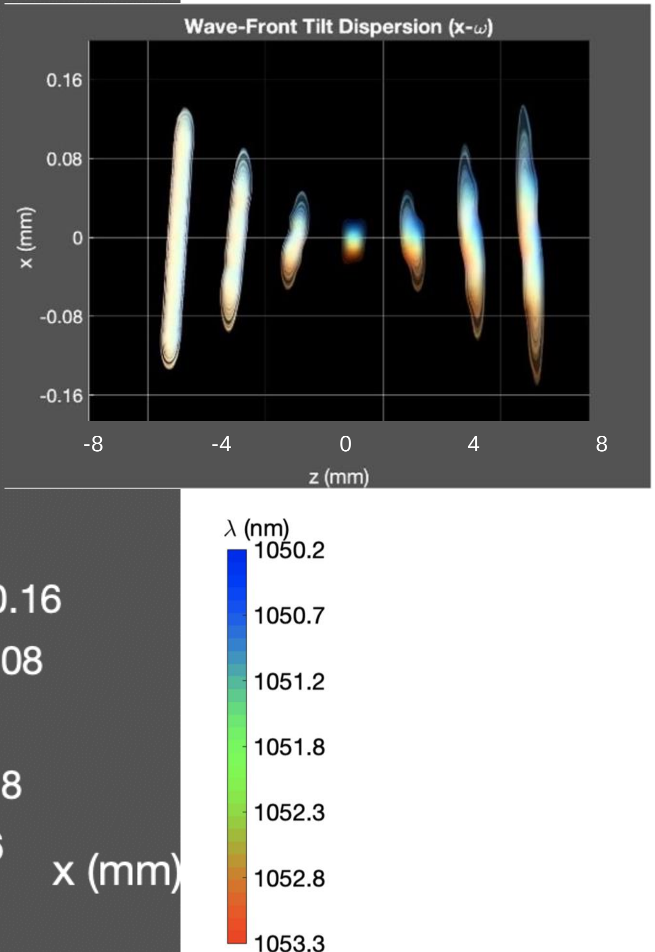
But we know from VBL simulations that spatiotemporal distortions must exist on NIF-ARC.



The simulated strength of coupling is lower than observed values at COMET.

Are there other distortions that we could be missing?





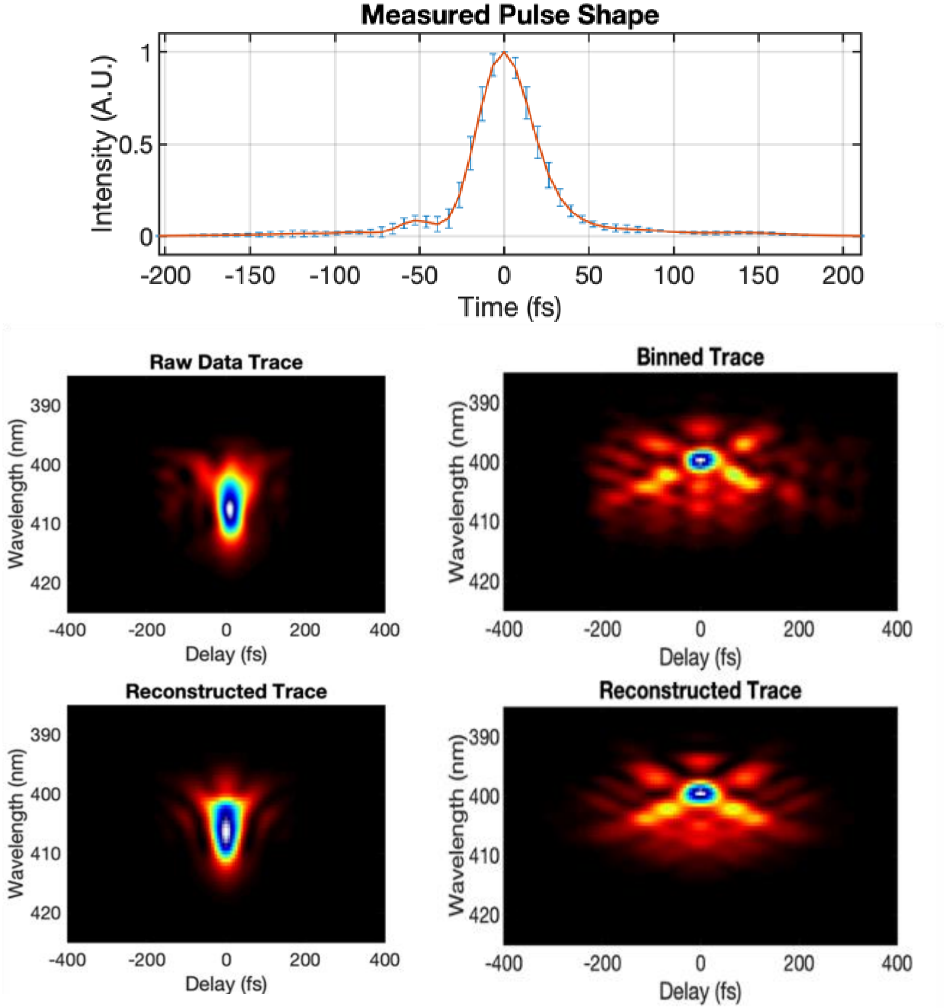
STRIPED FISH can identify and help to mitigate distortions in the pulse.

This talk covers advances in high-precision laser electric field measurements and control.

High-intensity, on-shot laser electric field measurement

Temporal structuring for optimization of laser-driven particle sources

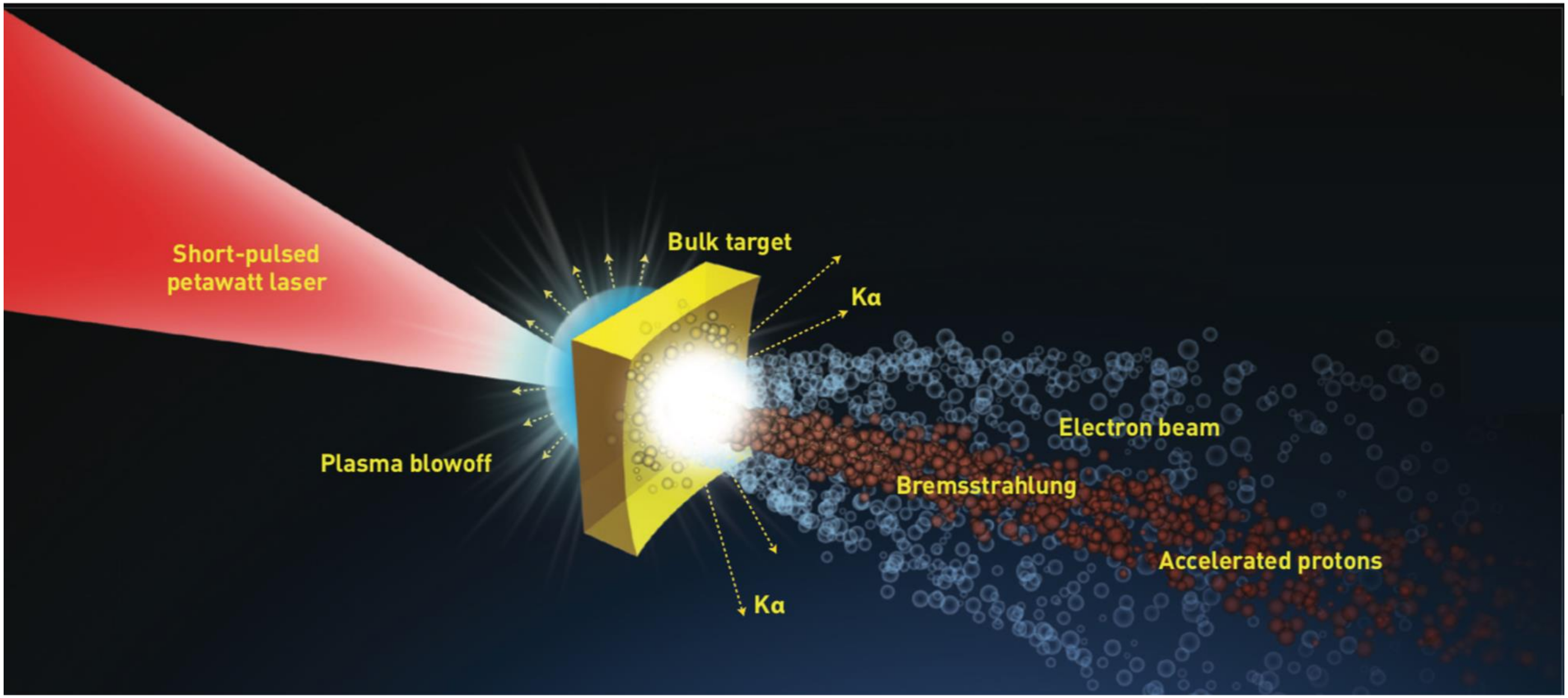
Spatiotemporal structuring of laser intensity and phase to generate optical vortices



Data from CSU laser system (2021).

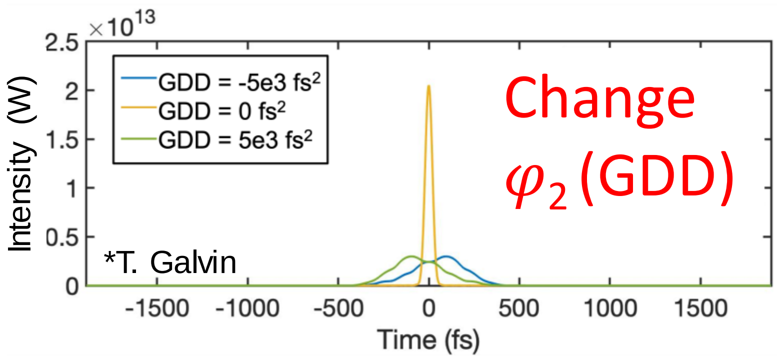
Ultrashort (<ps) temporal structuring may benefit laser-driven ion acceleration.

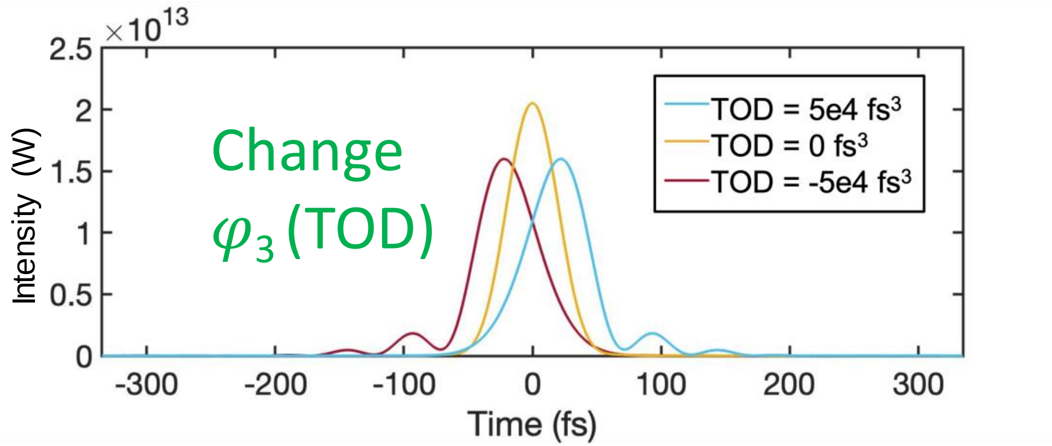
- In the most common scheme for ion acceleration, target-normal sheath acceleration (TNSA), a high-intensity laser irradiates a solid target to produce beamlike accelerated ions from the rear surface.



Temporal structuring of laser pulses can be achieved through laser spectral dispersion tuning.

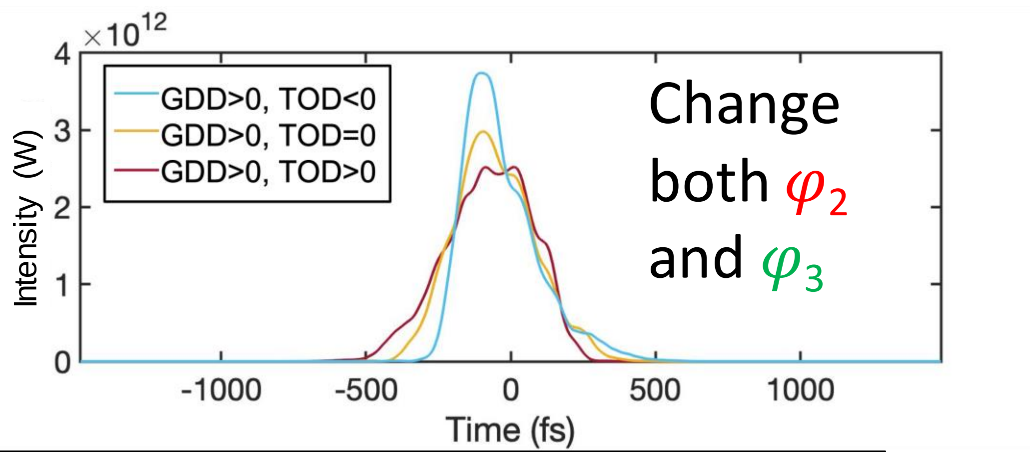
Laser spectral phase: $\varphi(\omega) = \varphi_0 + \varphi_1(\omega - \omega_0) + \varphi_2(\omega - \omega_0)^2/2 + \varphi_3(\omega - \omega_0)^3/6 + \ldots$





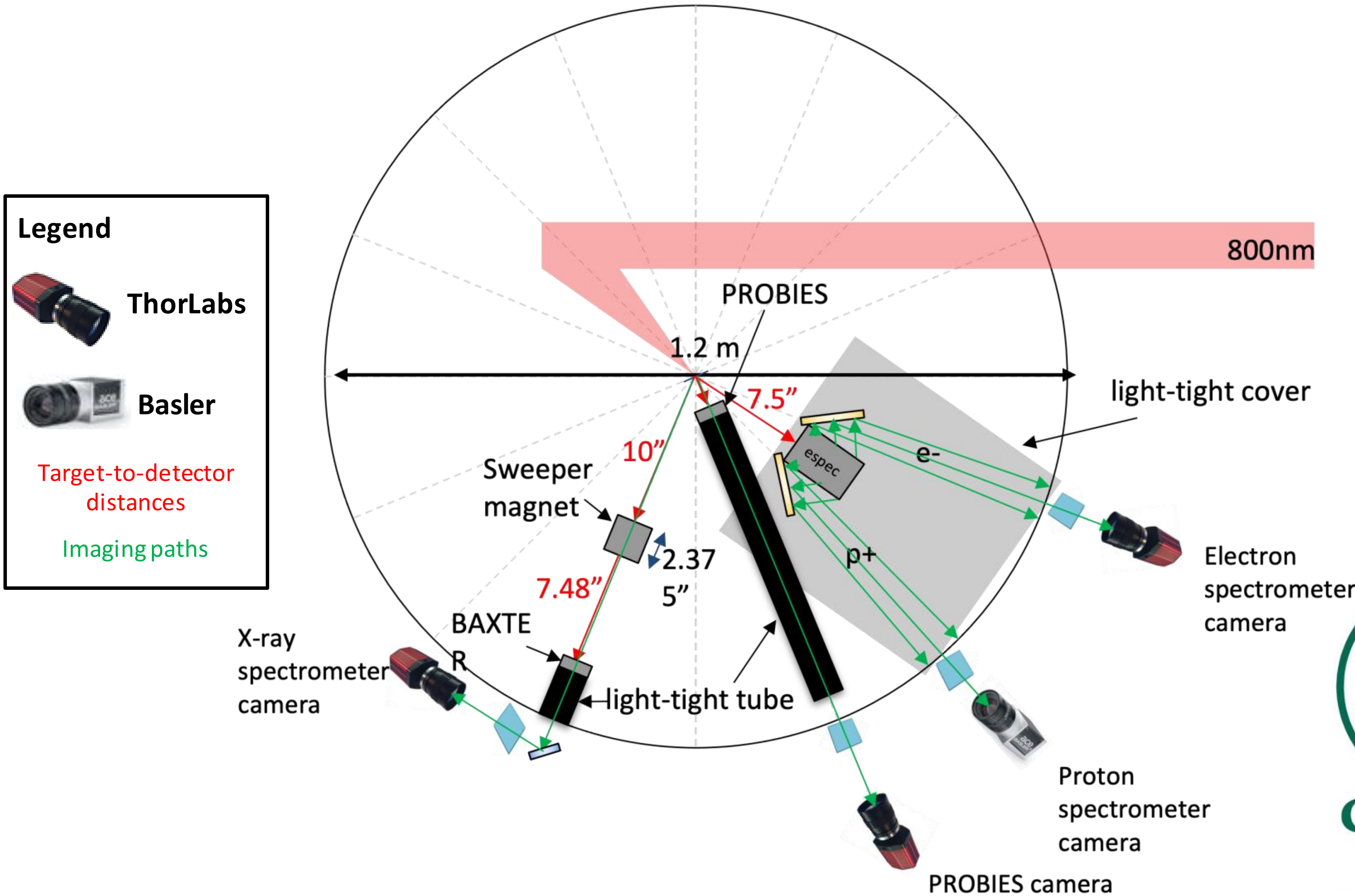
GDD: group delay dispersion, or second order dispersion

TOD: third order dispersion



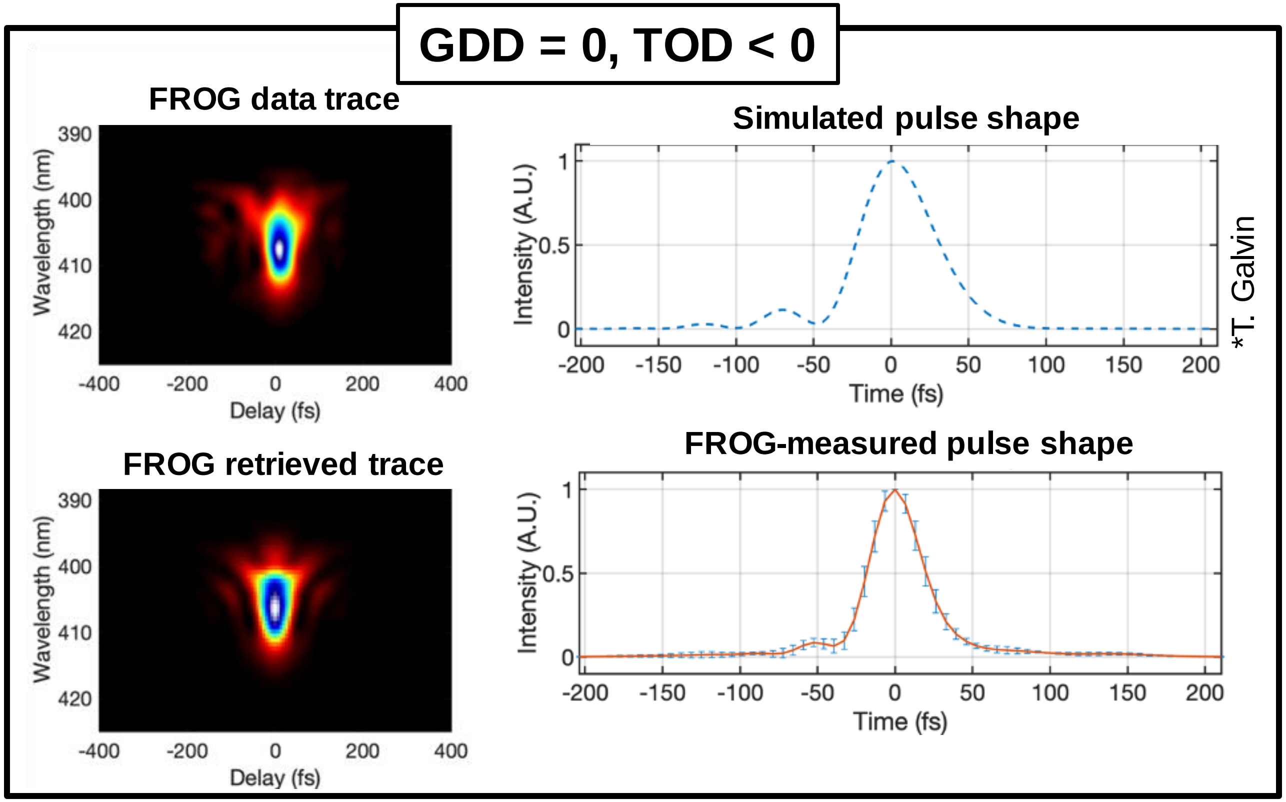
We can both accurately manipulate and measure the temporal pulse shape.

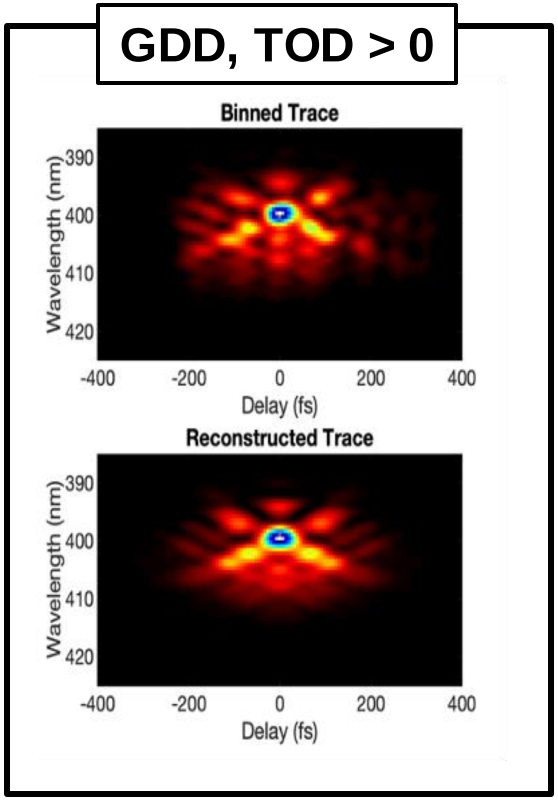
We ran an experiment at ALEPH laser through LaserNet to explore temporal pulse shaping for ion acceleration



Experimental validation of pulse shape control at CSU completed via FROG traces with 3fs resolution.

FROG: Frequency Resolved Optical Gating

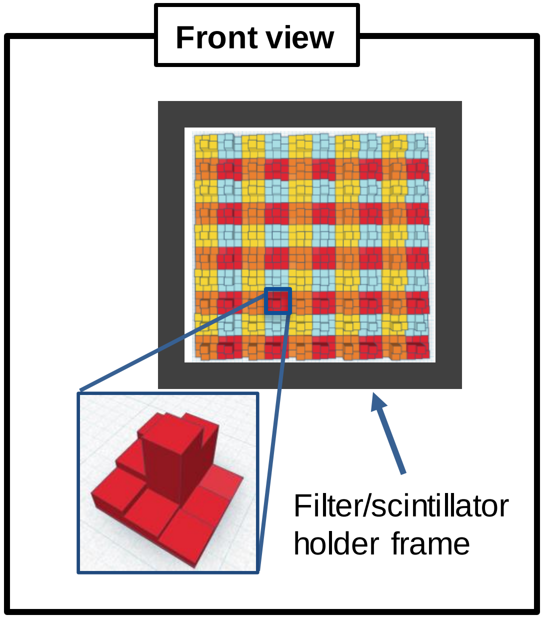


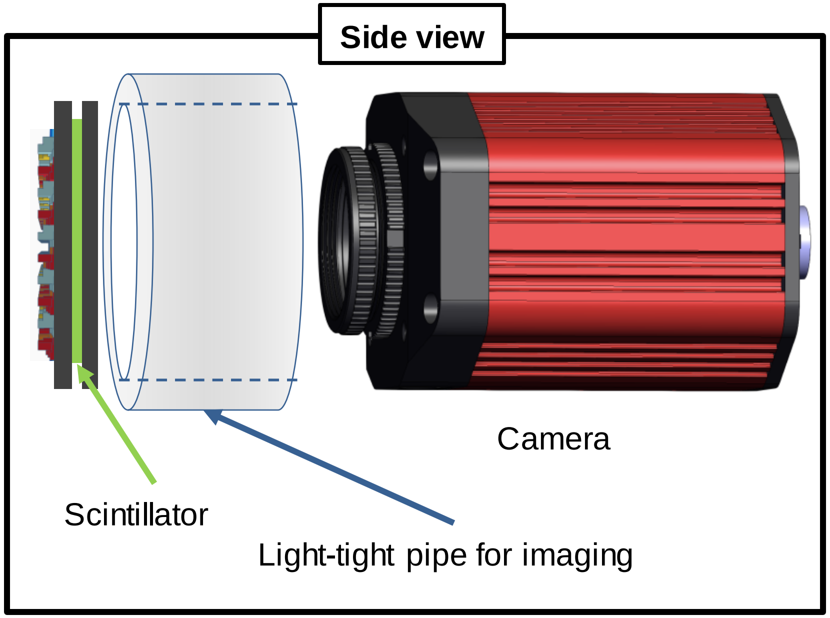


FROG, which measures the temporal intensity and phase, also provides the spectral phase measurement for STRIPED FISH.

PROBIES provides simultaneous spatial and energy resolution of the proton beam at a high repetition rate.

<u>PROBIES (PROton Beam Imager and Energy Spectrometer)</u>



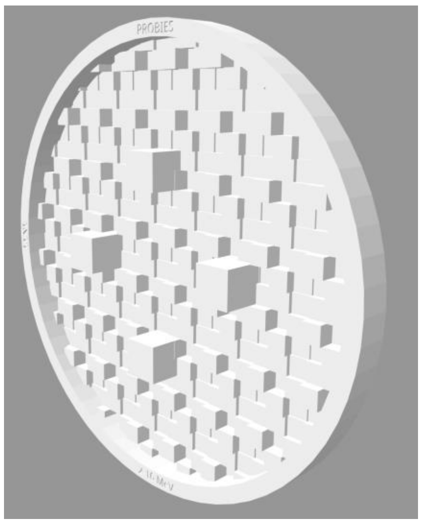


*D. Mariscal, B. Djordjevic, E. Grace, *et al.* PPCF (2021)

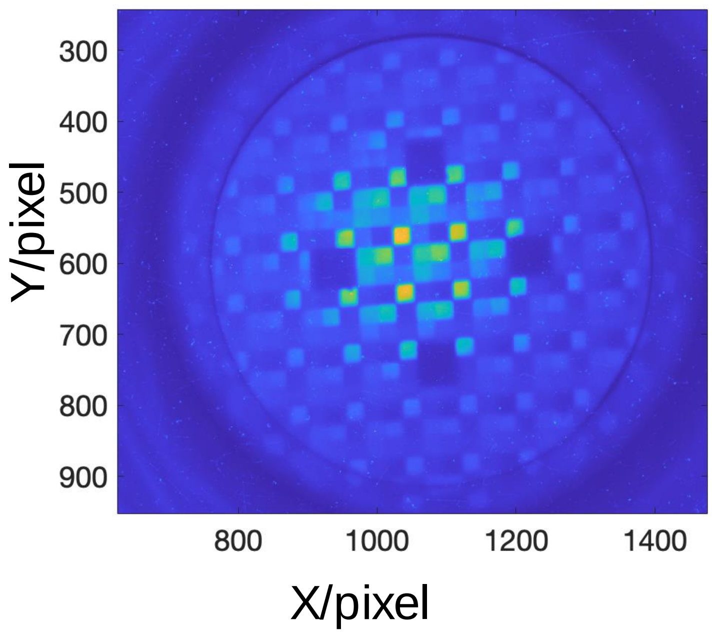
PROBIES can be used at a high repetition rate and does not require RCF stacks to operate, replacing the films with a digital detector.

High-rep-rated PROBIES setup enables rapid analysis

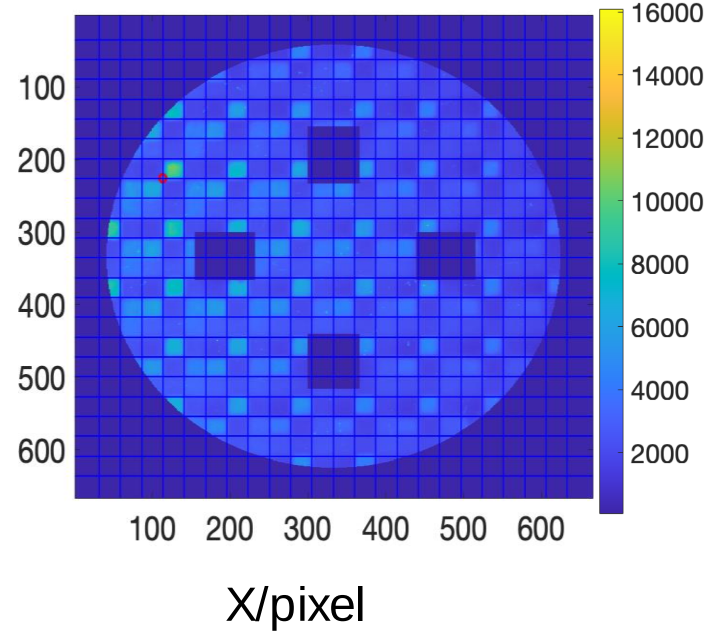
PROBIES Mask



Raw data

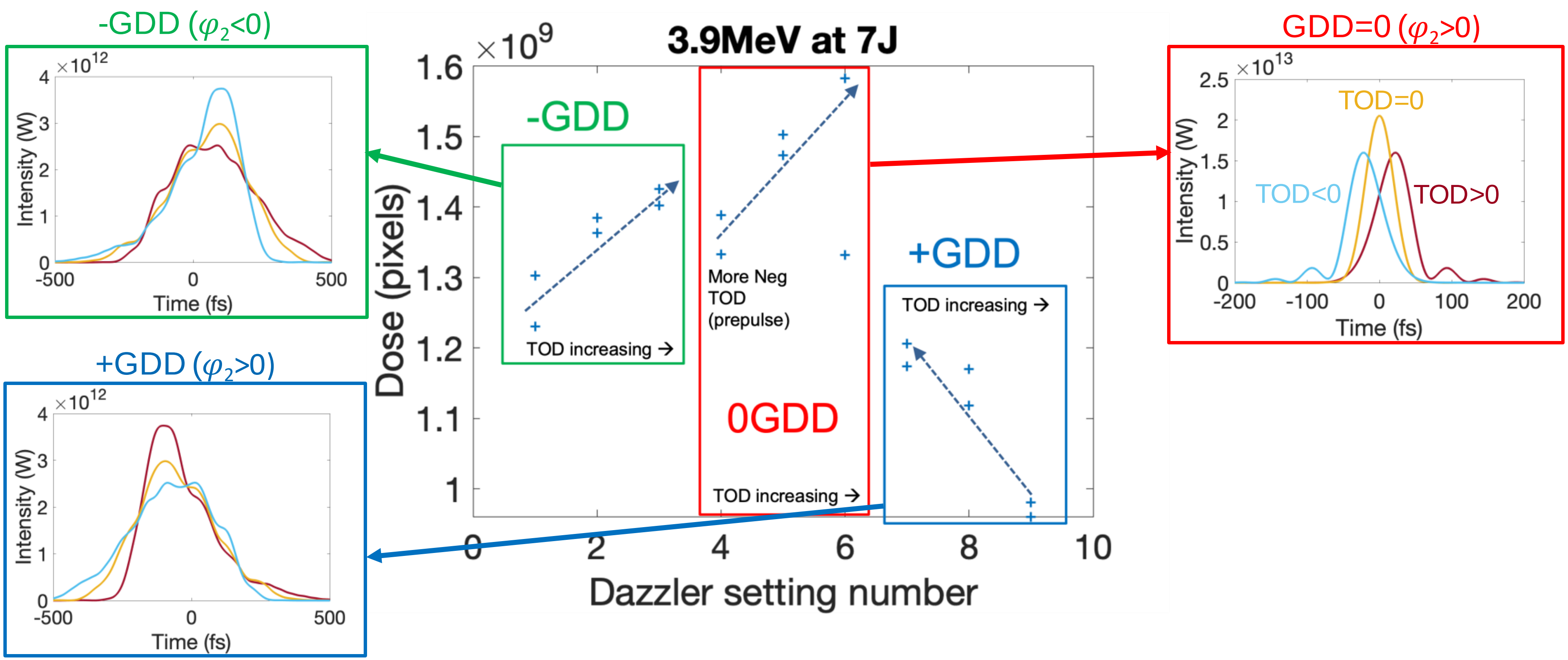


Grid registration



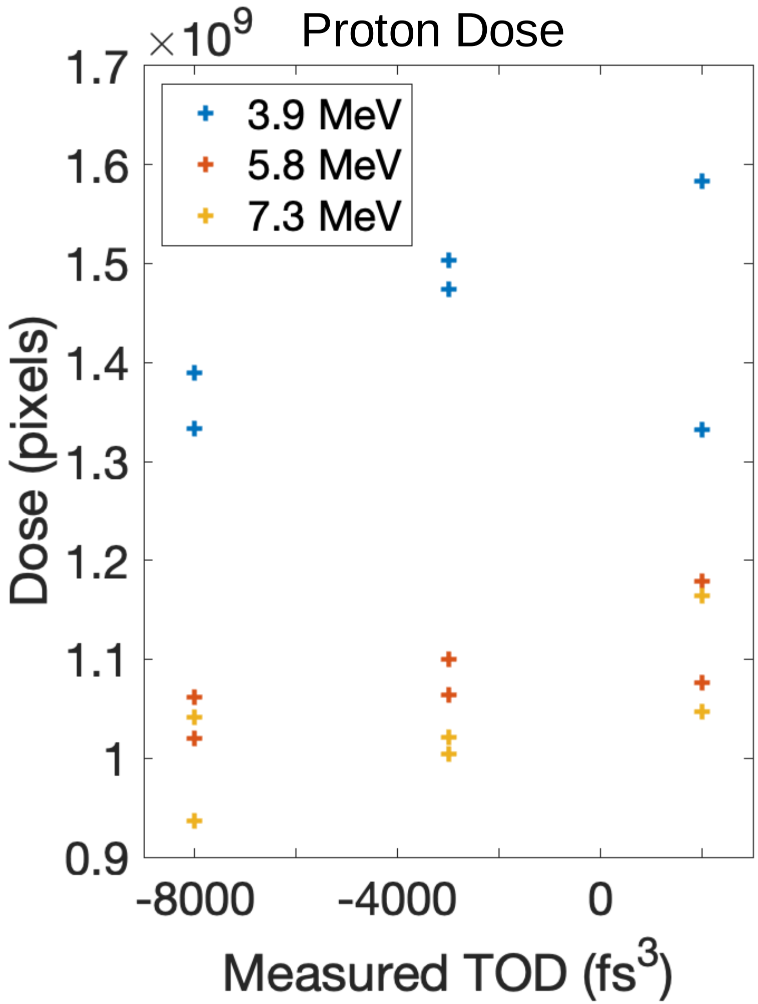
Spectral dispersion appears to be a strong tuning knob on proton dose

Laser spectral phase: $\varphi(\omega) = \varphi_0 + \varphi_1(\omega - \omega_0) + \varphi_2(\omega - \omega_0)^2/2 + \varphi_3(\omega - \omega_0)^3/6 + \ldots$



The highest dose was obtained when the third order dispersion was positive, creating a post-pulse.

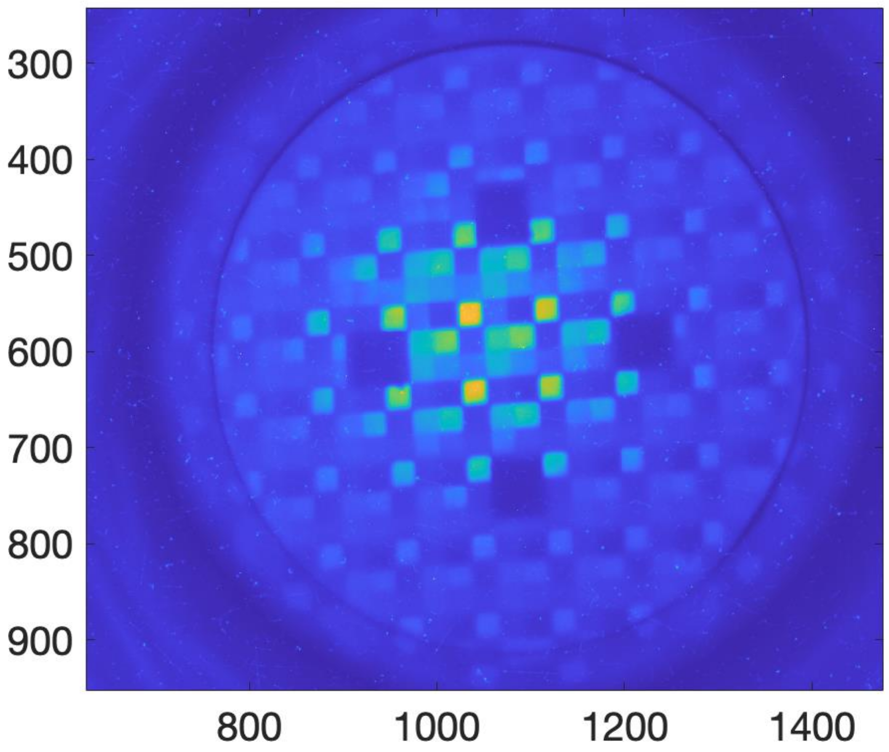
Our results show promising dispersion tuning effects, especially with third order dispersion



- 48 spectral phase shaping shots were taken on one day at CSU.
- On the left, the results from the 7J scan are plotted for proton energies from 3.9 to 7.3 MeV.
- Third order spectral phase improved proton dose when the second order spectral phase was close to zero.
- This pattern persisted up through 7.3MeV, when proton dose dropped off.

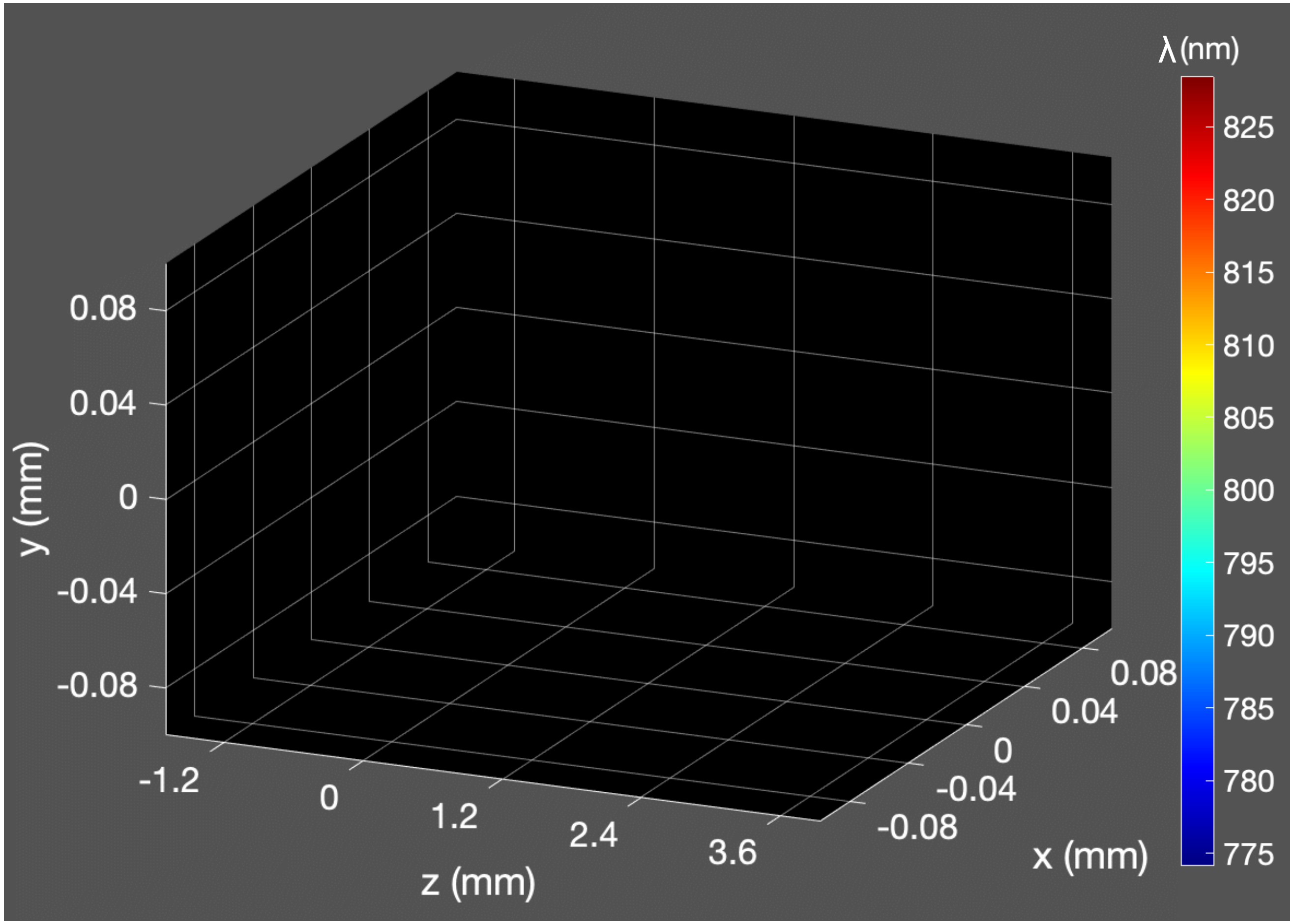
Future work involves recently completed beam time to further explore this relationship between spectral phase and proton dose.

- Second LaserNet experiment time recently completed (Dec 2022) to further explore this work and expand laser parameter scan
- Ensemble simulations for interpretation of results
- Comparison to other diagnostics and calibration of PROBIES diagnostic
- PROBIES analysis can be used in feedback loop and to enable transfer learning



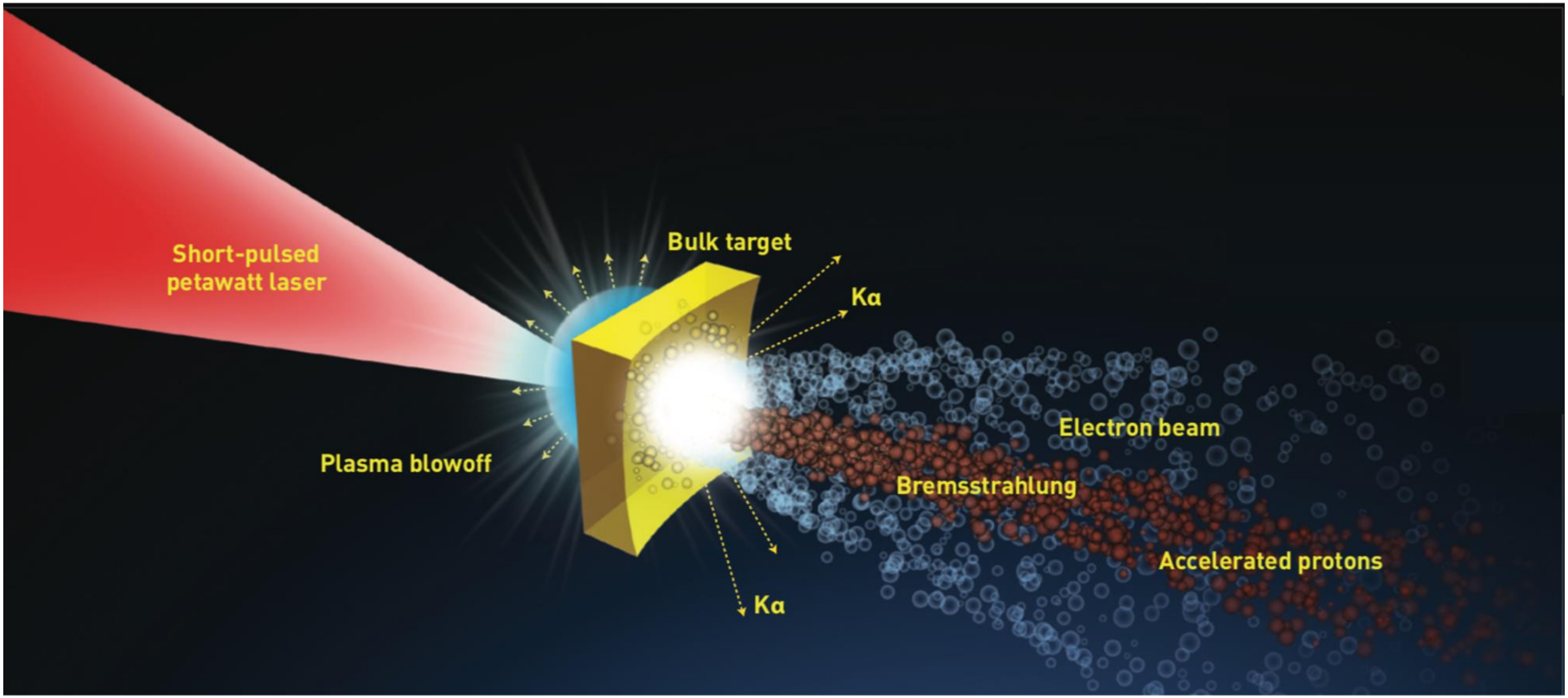
And finally, I will bring all of these capabilities together for a new experiment.

- High-intensity, on-shot laser electric field measurement
- Temporal structuring for optimization of laser-driven particle sources
- Spatiotemporal structuring of laser intensity and phase to generate optical vortices



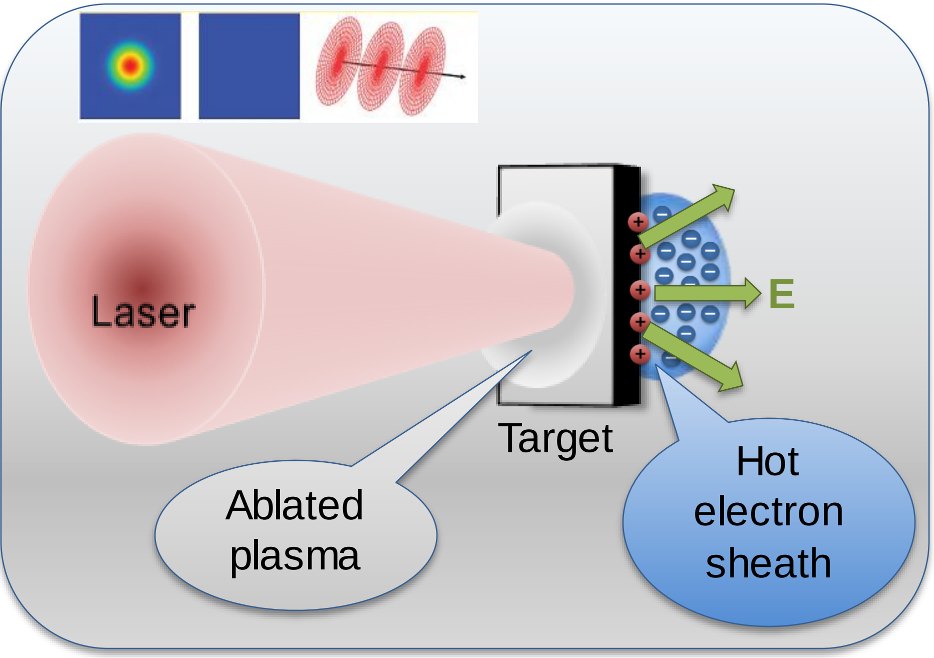
Simulation by E. Grace

Optical vortices may benefit TNSA by providing a tailored electron sheath for ion acceleration.

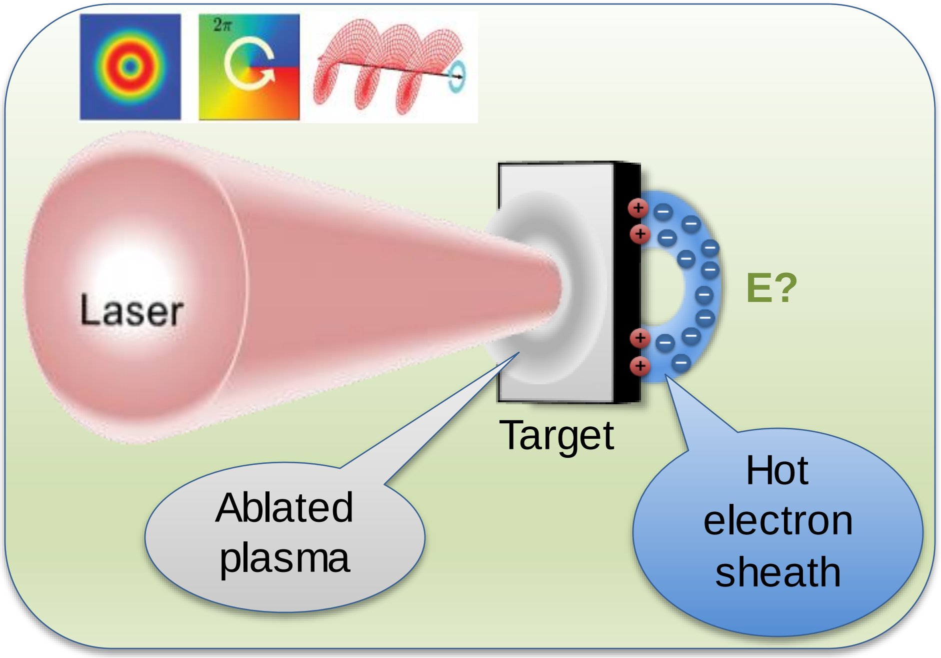


Ion acceleration processes such as TNSA can benefit from advances in laser technology.

TNSA with a Gaussian Pulse

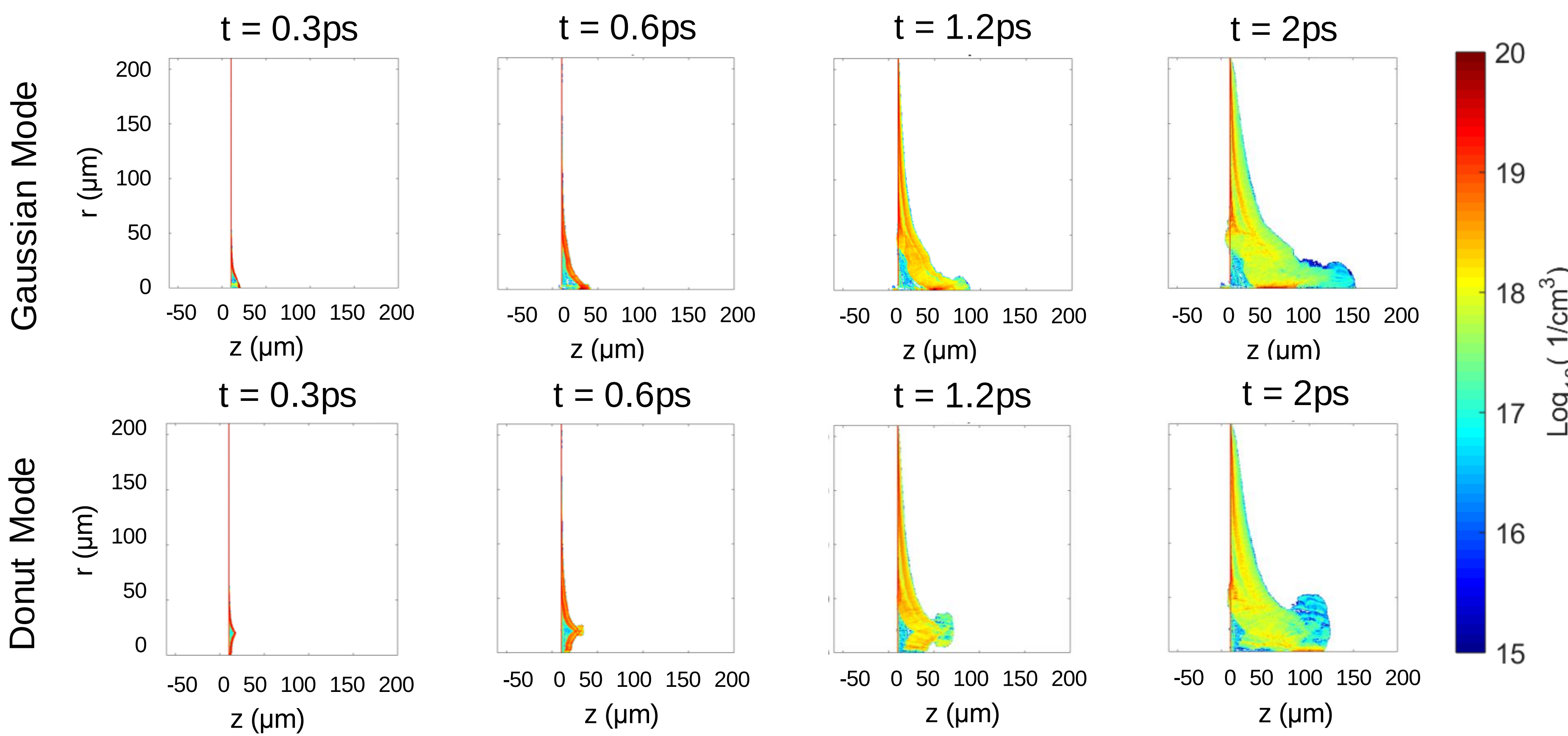


TNSA with a Donut Laser Pulse



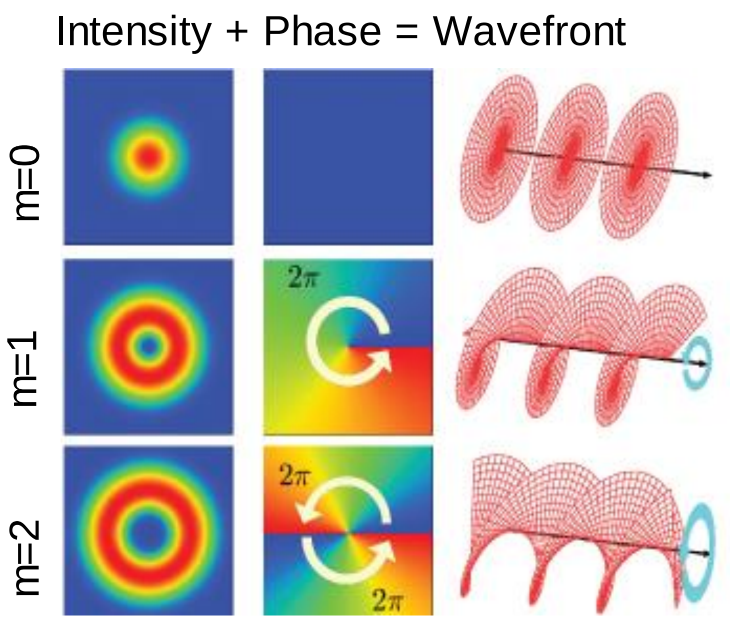
How can we use structured light to tailor our particle acceleration?

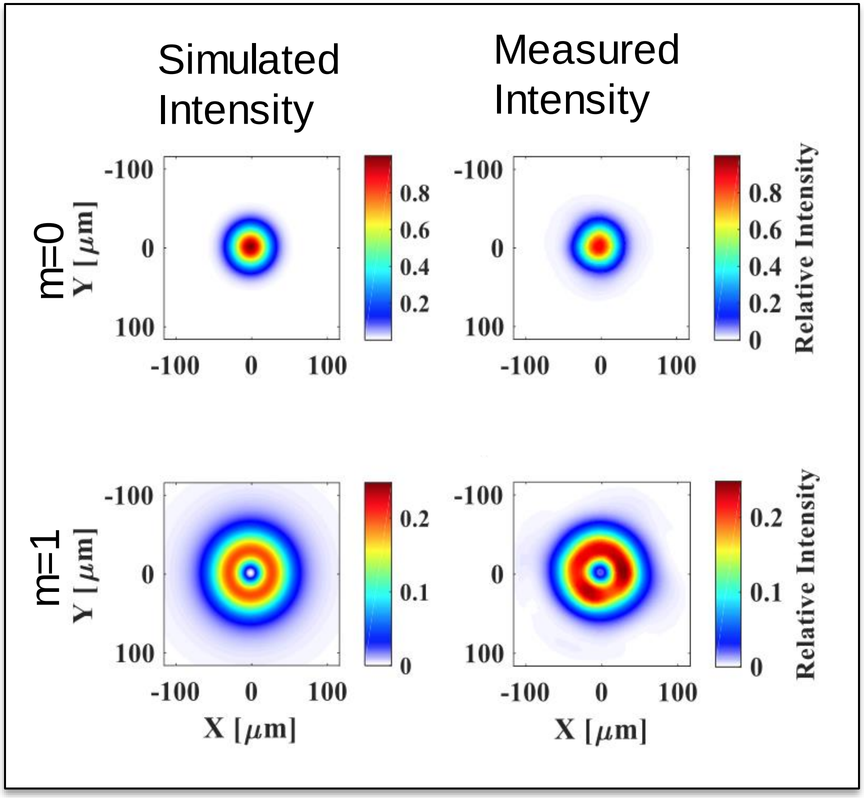
Preliminary simulations compare proton distribution over time for Gaussian and donut modes



*Simulations by J. Kim

How can we create high-intensity optical vortices?



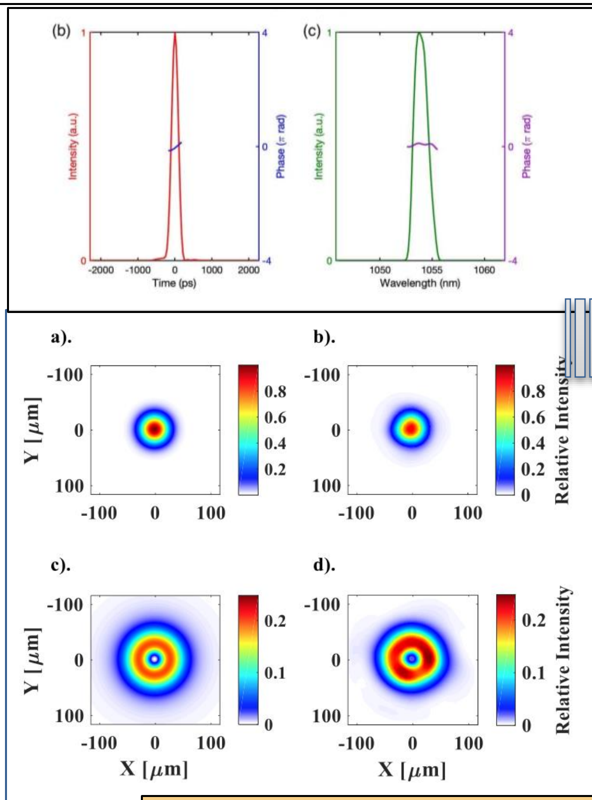


A. Longman *et al*, Opt. Lett. (2020).

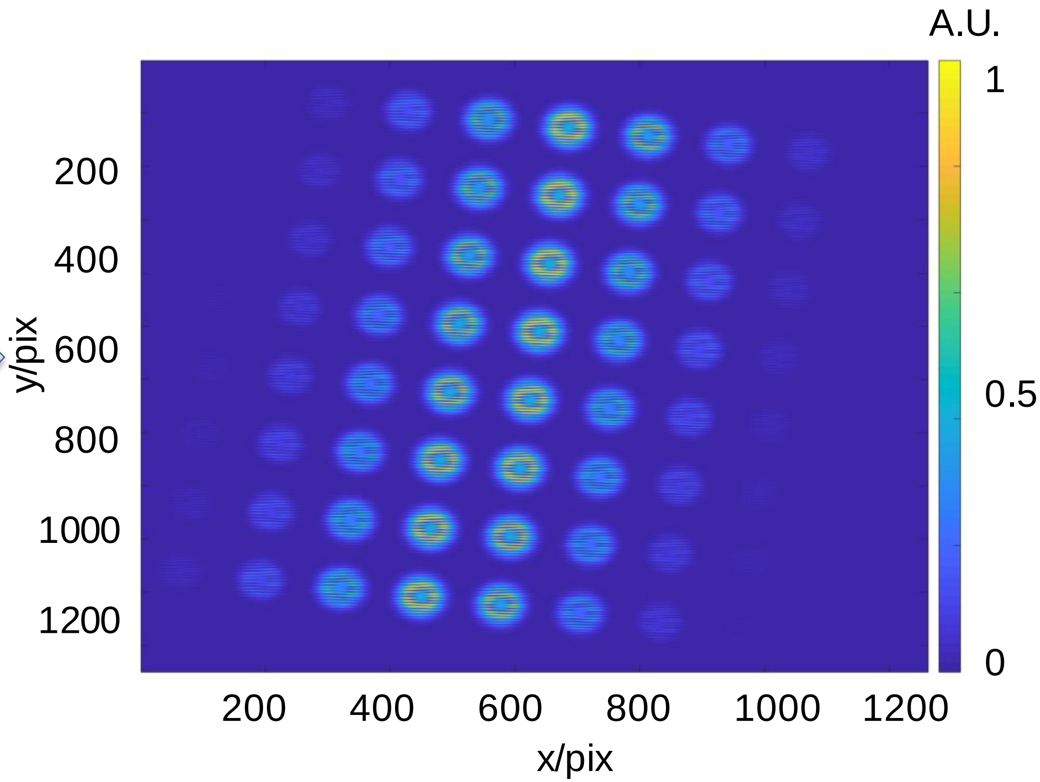
Off-axis spiral phase mirrors, which we are making now in collaboration with the MRF at Livermore, show promise for generating high-intensity optical vortices but must be validated.

Current validation methods have been limited to spatial and temporal measurements taken separately.

Currently, validation of the high-intensity optical vortex has been limited to space and time measurements taken separately.

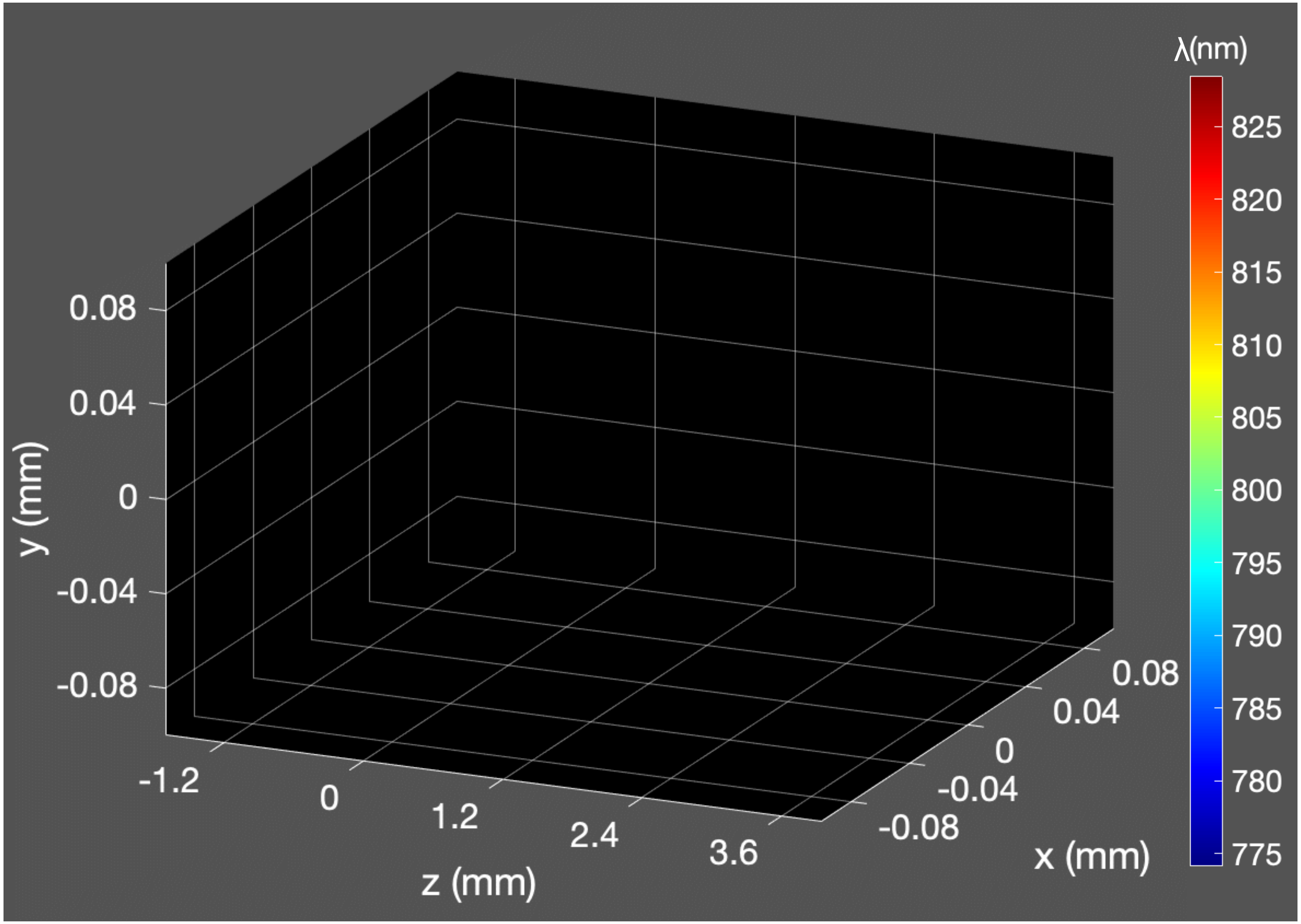


However, the defining feature of an optical vortex is the spiral spatial phase, which would be measured on-shot with STRIPED FISH.

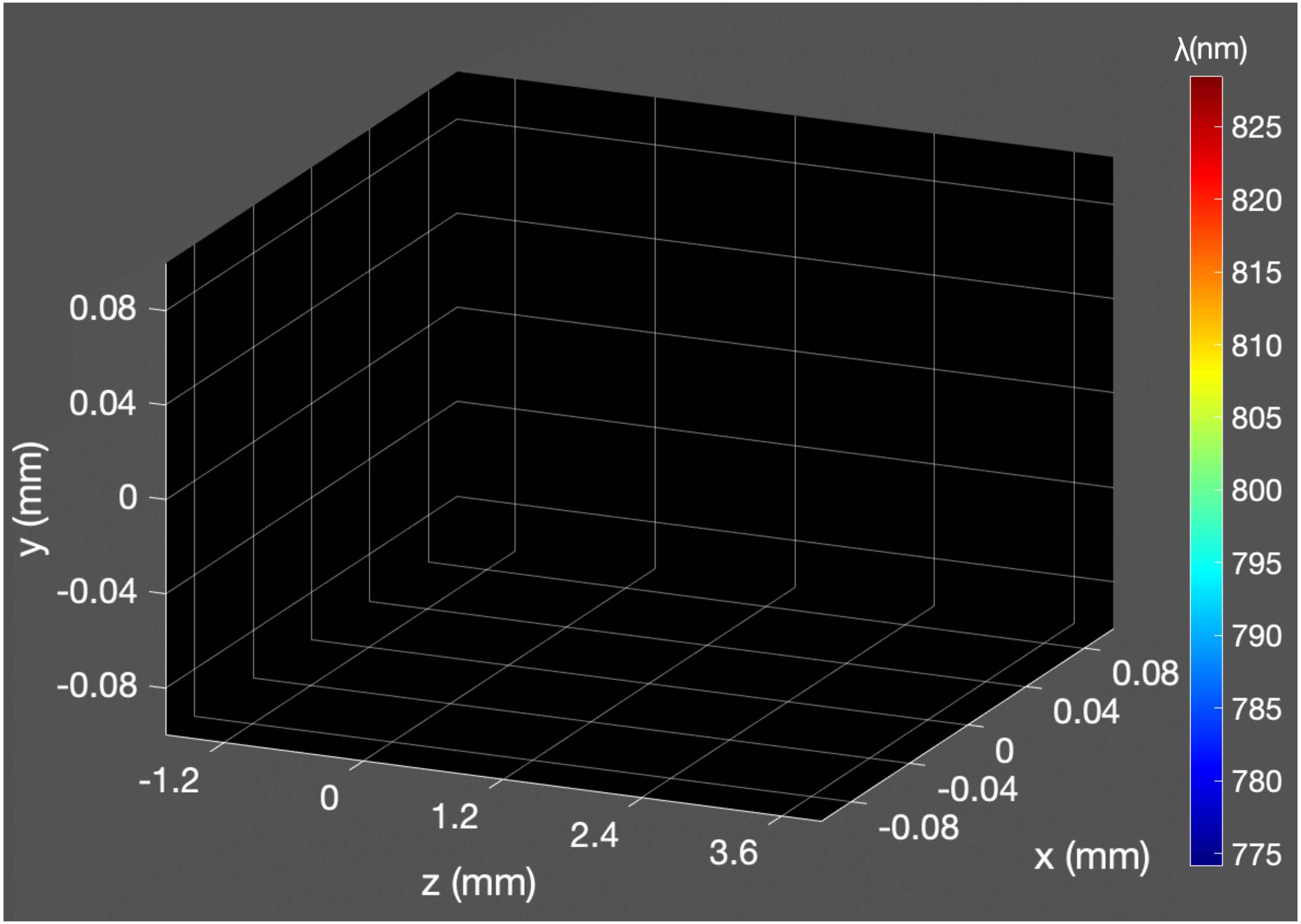


STRIPED FISH provides the first high-intensity measurement of the spatiotemporal phase that defines optical vortices.

However, without spatiotemporal validation, we will not know whether we are generating a simple optical vortex

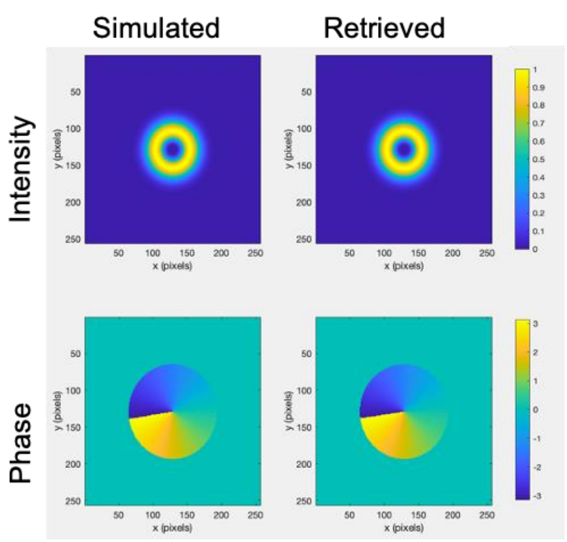


…or a spatiotemporally perturbed beam with no characteristic ring shape at the focus.

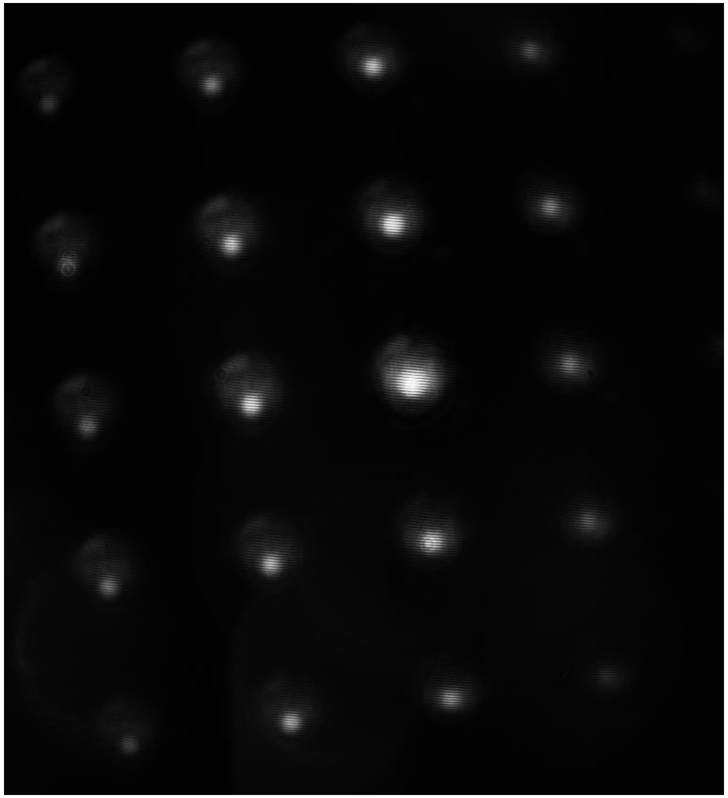


This work is ongoing with a recent LaserNet proposal awarded for BELLA.

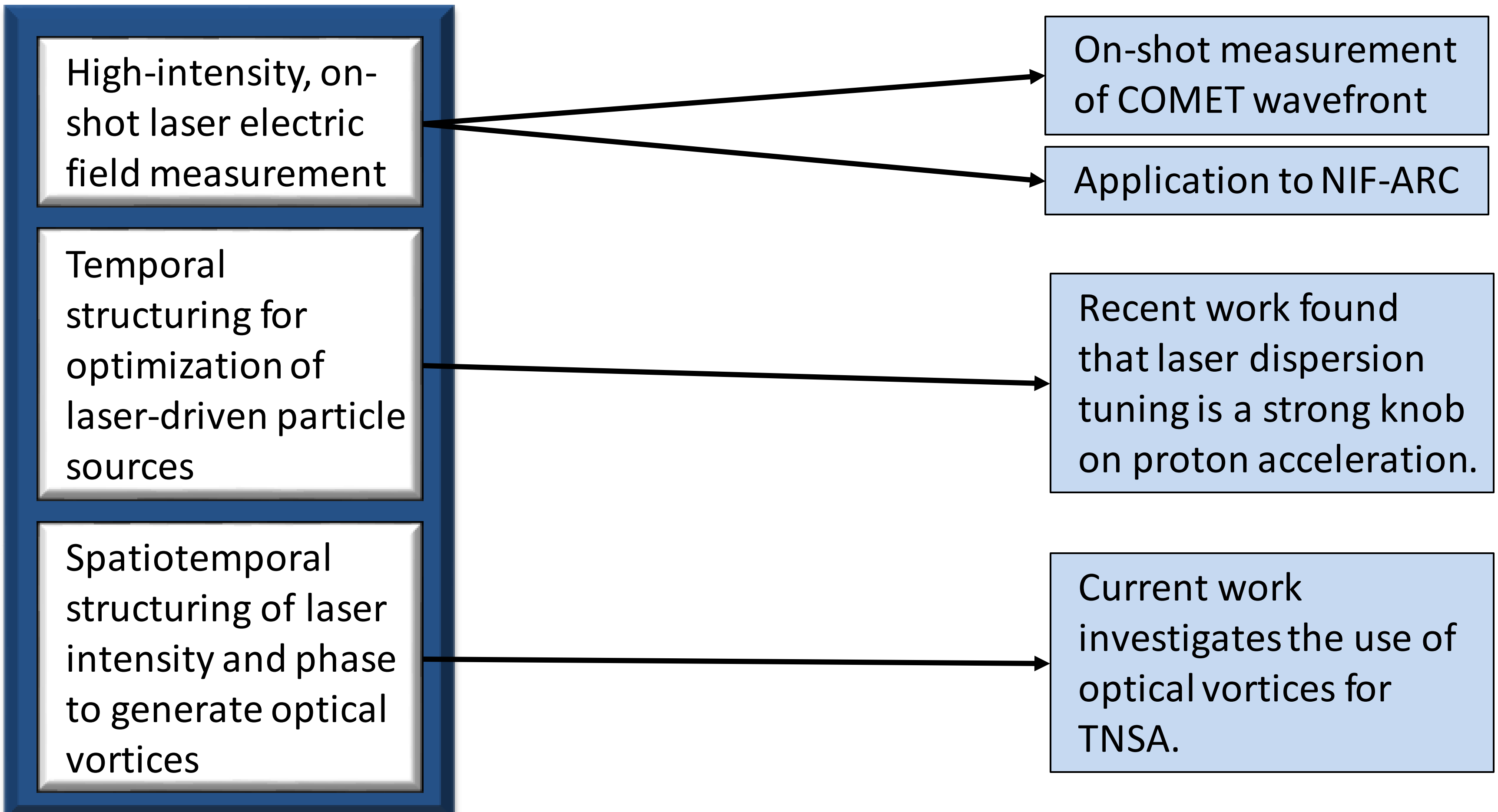
- STRIPED FISH has been built at BELLA and is in place retrieving the spatiotemporal distortions on-shot.
- The experiment is scheduled for May 2023 and funded for $25k (PI: E. Grace, K150)



Raw STRIPED FISH trace at BELLA



In summary, this talk discussed laser metrology for precision-controlled secondary sources.



Lawrence Livermore National Laboratory