Laser Temporal Shaping for Minimizing Emittance in High Brightness Applications

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Outline

Dispersion Controlled Nonlinear Synthesis

- Temporal Shaping via Noncolinear Sum Frequency Mixing
- LCLS-II Photoinjector

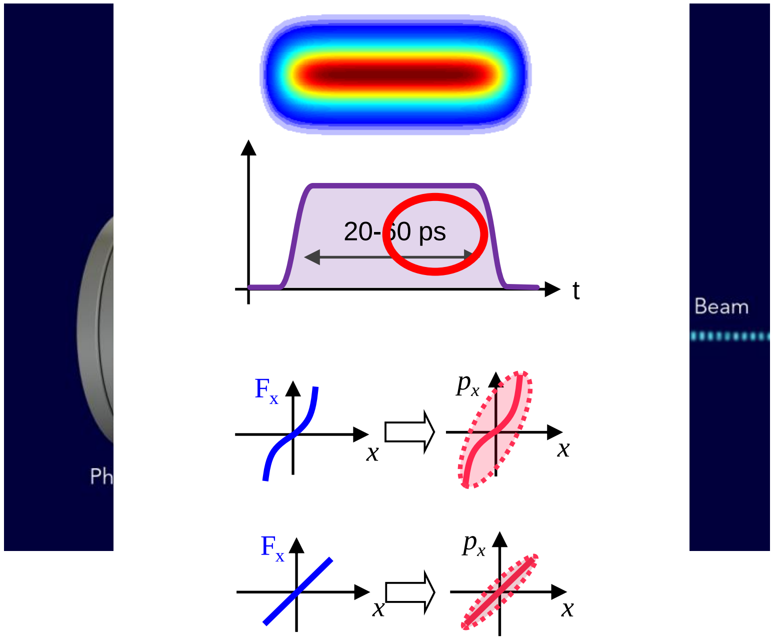
Programable Shaping with DCNS

Four Wave Mixing for Direct Shaping at any Wavelength

Dispersion Controlled Nonlinear Synthesis

Temporal Shaping and Emittance Reduction

Emittance Reduction



- Electron beam performance dependent on laser shape
- Sudo-flattop laser shape with smooth profile optimizes for reduced emittance
  - Serafini, L. and Rosenzweig, J.B., 1997. *Physical Review E, 55*(6), p.7565
  - Krasilnikov, M., et al., 2012. *Physical Review Special Topics-Accelerators and Beams* 15(10), p.100701
  - O. Luiten et al., 2004. *Physical Review Letters* 93, p.094802
- LCLS-II asks for 20-60 ps flattop in the UV
- “Easy” avenue forward towards achieving high fidelity x-ray beams

The Picosecond Shaping Problem

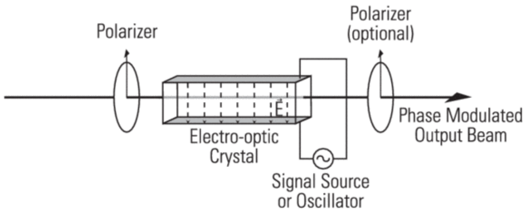
Temporal Amplitude Shaping

- Direct modification of electric field amplitude as a function of time
- Limited by the temporal resolution and duration of the driver (typically >ns)
- Ultrashort pulses (<ps) intrinsically fall outside this domain

Spectral Shaping

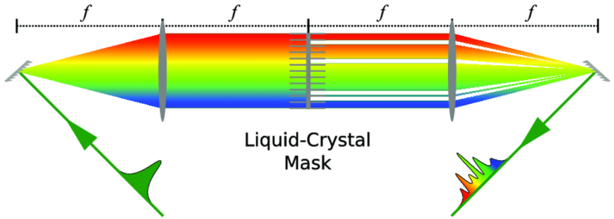
- Modification of amplitude or phase of the spectral components
- Limited by spectral resolution of device (~0.1 nm) and bandwidth of laser pulse
- A transform limited 800 nm 1ps pulse only has ~1 nm bandwidth (10ps => 0.1 nm)

Temporal shaping in the 10s ps - 100s ps is inaccessible with current technologies



https://www.newport.com/n/practical-uses-and-applications-of-electro-optic-modulators

https://fastlite.com/produits/dazzler-ultrafast-pulse-shaper/



Savolainen, Janne. (2008). Coherent Control of Biomolecules.

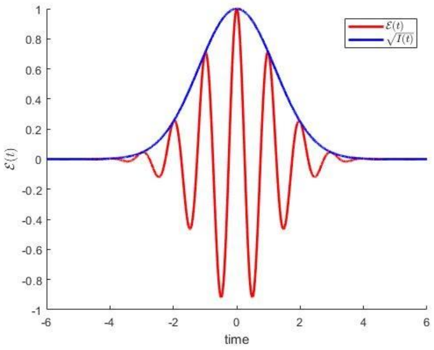
DCNS Theoretical Overview

Spectral Phase in Broadband Optical Pulses

Electric field of a pulse:

$$\mathcal{E}(t) \propto \frac{1}{2}\sqrt{I(t)}e^{i[\omega_0 t - \phi(t)]} + c.c.$$

- *I(t)* is the intensity
- ω_0 is the central frequency
- *Φ(t)* is the (temporal) phase



$$\tilde{\mathcal{E}}(\omega) = \sqrt{S(\omega)}e^{-i\varphi(\omega)}$$

- *S(ω)* is the spectrum
- *φ(ω)* is the spectral phase

$$\varphi(\omega) = \varphi_0 + \varphi_1\frac{\omega-\omega_0}{1!} + \varphi_2\frac{(\omega-\omega_0)^2}{2!} + \varphi_3\frac{(\omega-\omega_0)^3}{3!} + \ldots$$

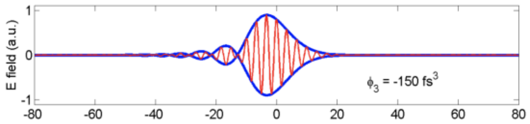
Spectral Phase in Broadband Optical Pulses

φ₀ Phase between pulse and carrier (Carrier Envelope Phase offset/**CEP**)

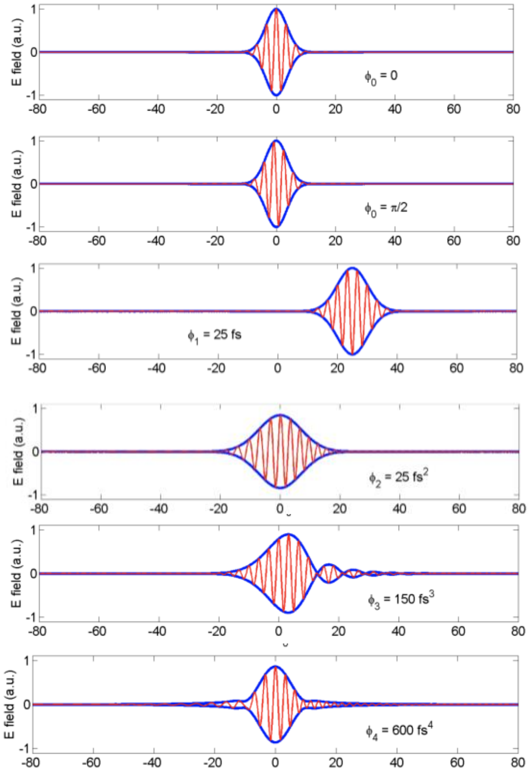
φ₁ Shift in time (Group Delay/**GD**)

φ₂ Linear chirp (positive or negative) where frequency changes linearly in time (GD Dispersion/**GDD** or second order dispersion/**SOD**)

φ₃ Quadratic chirp (positive or negative) leads to pre- or post-pulses in the temporal domain (third order dispersion/**TOD**)

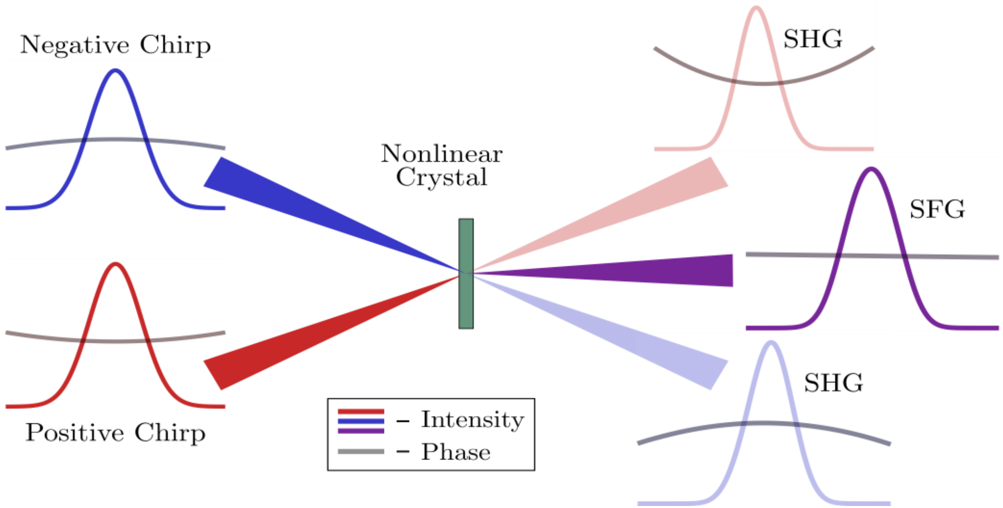


$$\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega - \omega_0}{1!} + \varphi_2 \frac{(\omega - \omega_0)^2}{2!} + \varphi_3 \frac{(\omega - \omega_0)^3}{3!} + \dots$$

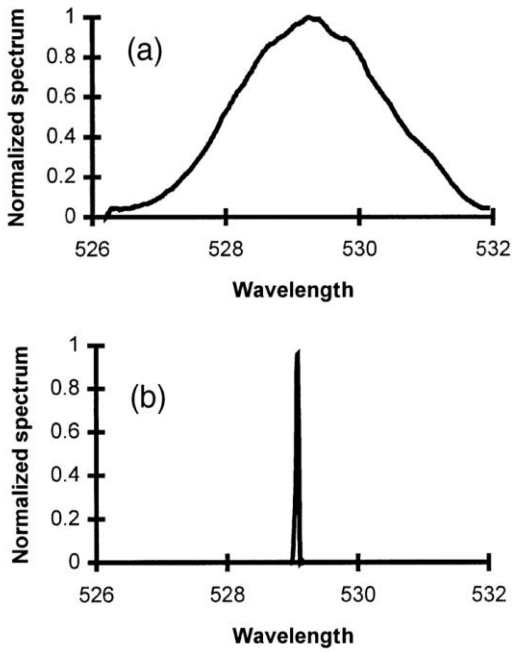


fs → ps | Broadband → Narrowband

- Stretch input pulses by applying large amounts of Opposite SOD
- Mix via SFG in a non-colinear fashion
- → ps near transform limited pulses



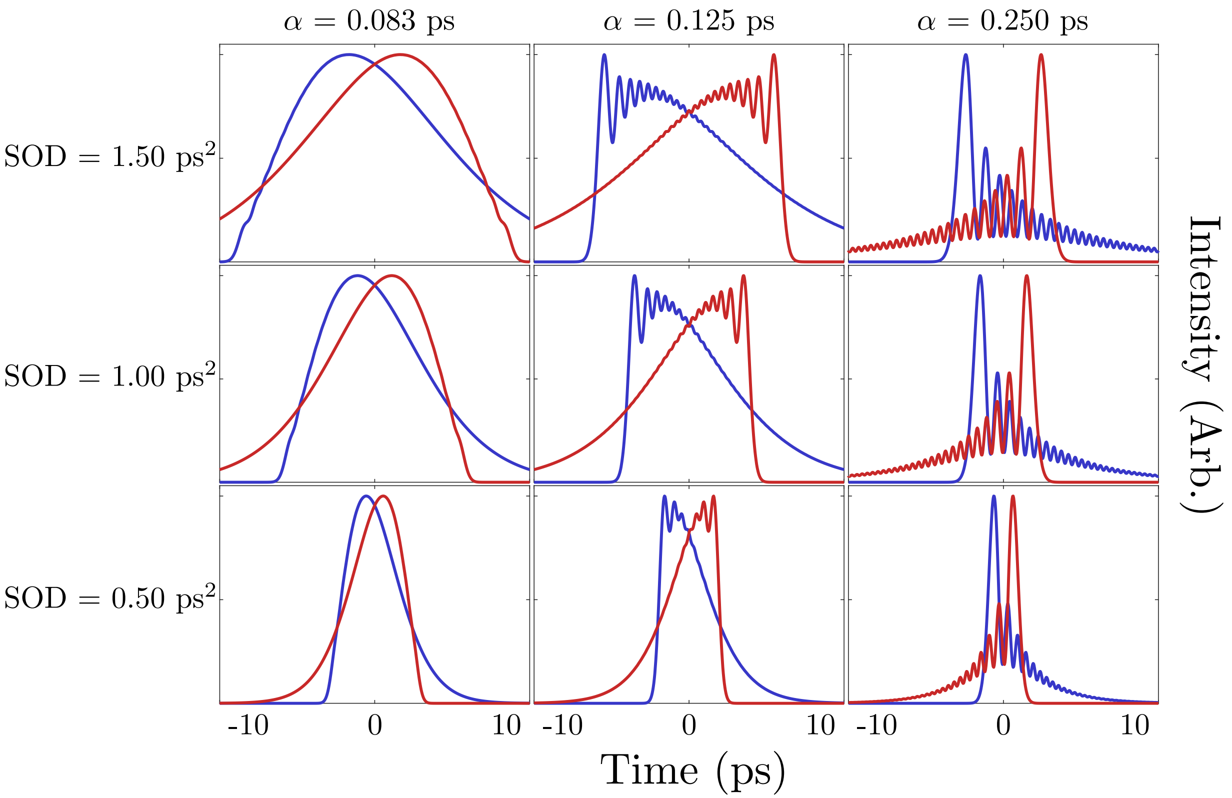
Lemons, Randy, et al. *PRAB* 25.1 (2022): 013401



Raoult et al. Opt. Lett. 23 (14) 1117 (1998)

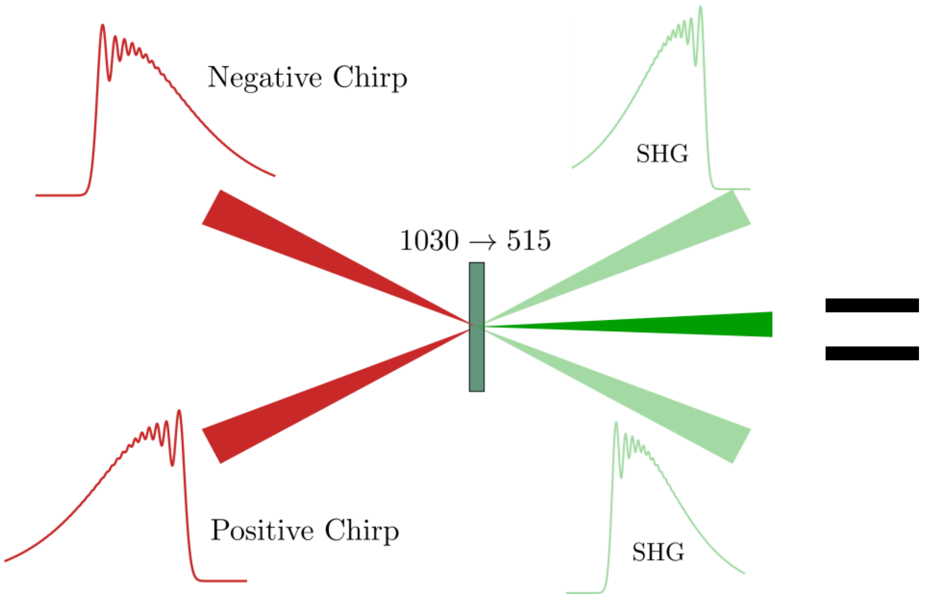
Ratio of TOD/SOD

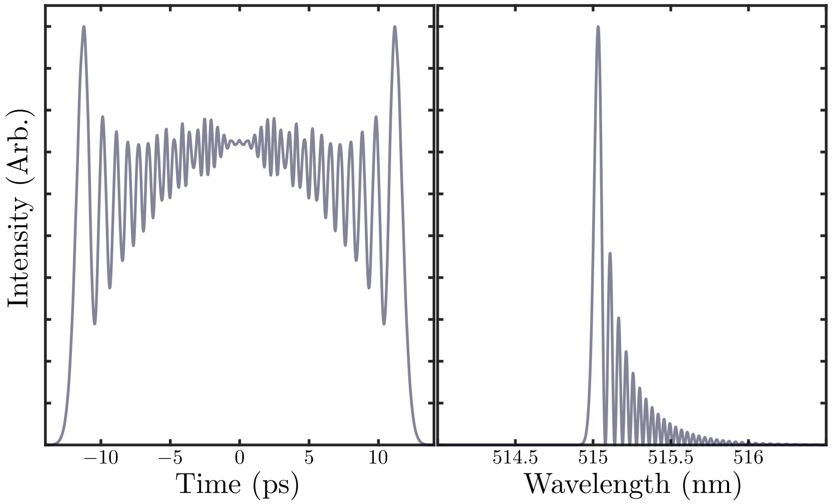
- Define ratio between TOD and SOD
  $$\alpha = \frac{TOD}{SOD}$$
- SOD roughly controls duration and α controls shape
- Looking for a square pulse shape, focus on $\alpha = 0.125\, ps$



LCLS-II: Flattop

Non-Colinear Mixing with TOD

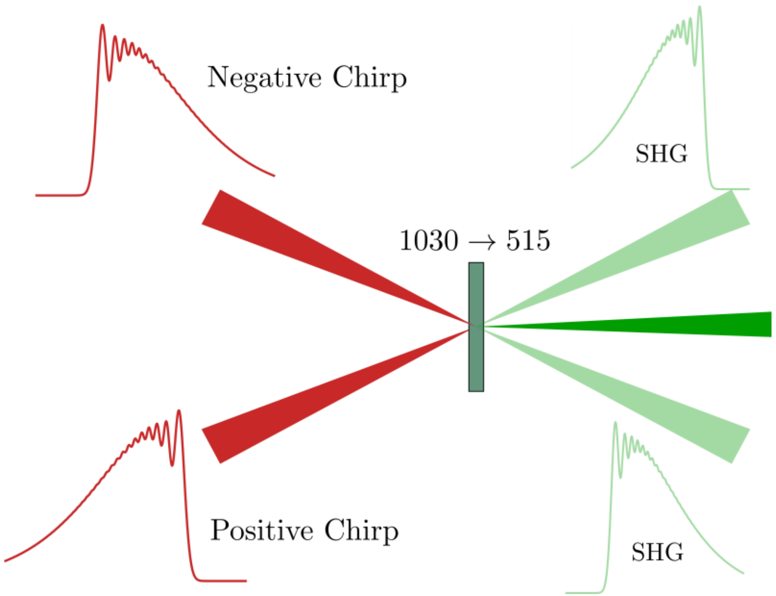




- $\alpha = \sim 0.125\ ps$
- $SOD = \sim 3.2\ ps^2$

Lemons, Randy, et al. *PRAB* 25.1 (2022): 013401

Diagrammatic Experimental Setup



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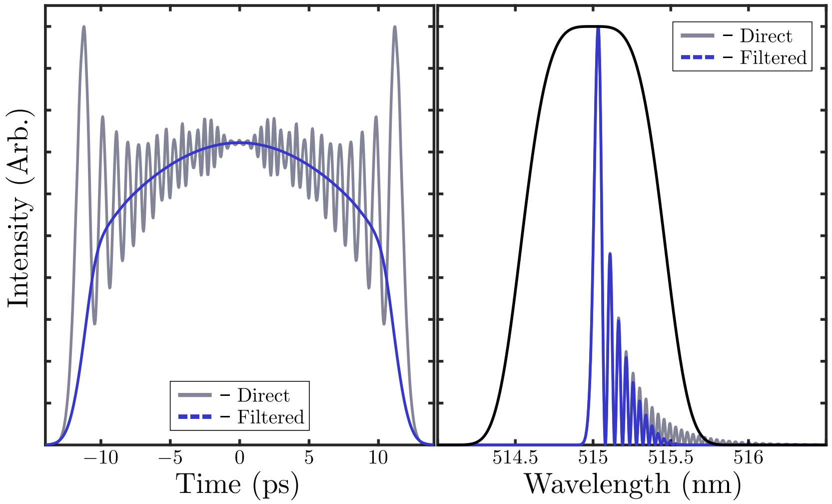
95% transmission



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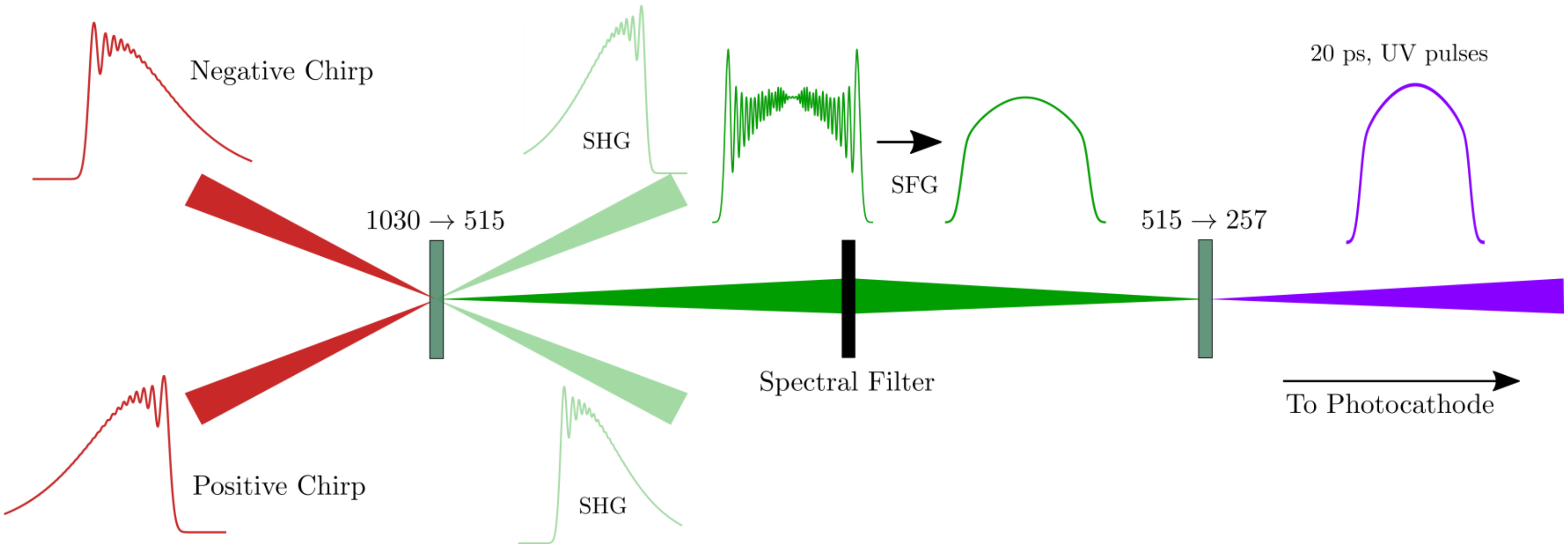
Lemons, Randy, et al. *PRAB* 25.1 (2022): 013401

Dispersion Controlled Nonlinear Synthesis (DCNS)



- $\alpha = \sim 0.125\ ps$
- $SOD = \sim 3.2\ ps^2$

Lemons, Randy, et al. *PRAB* 25.1 (2022): 013401

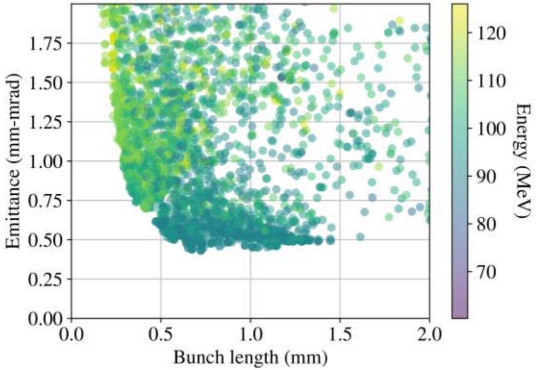
Theorized Photocathode Performance

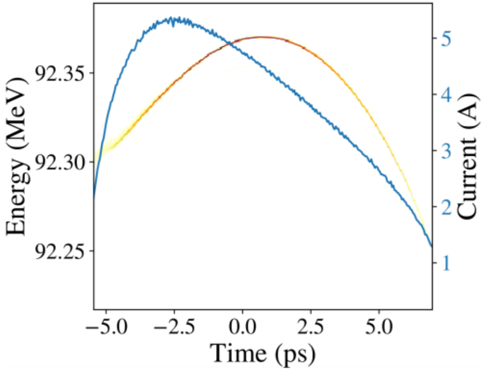
Transverse emittance at the end of the injector

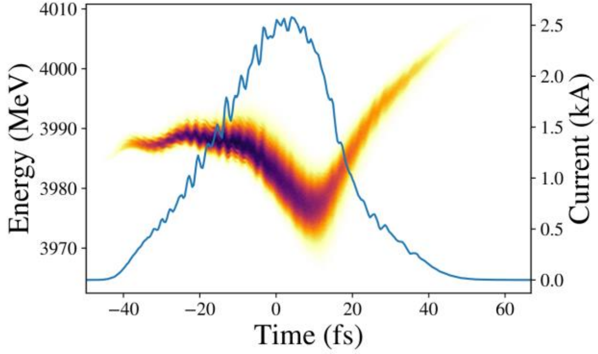
Bunch current at the end of the injector

Bunch current just before undulators

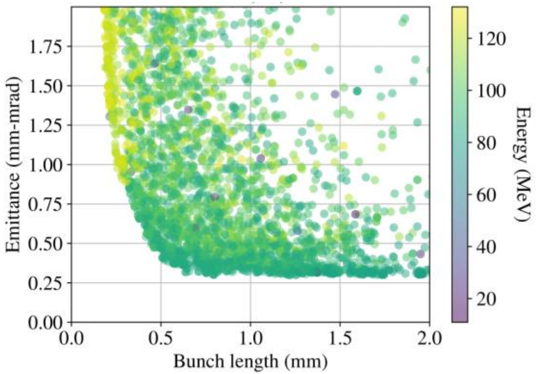
Gaussian

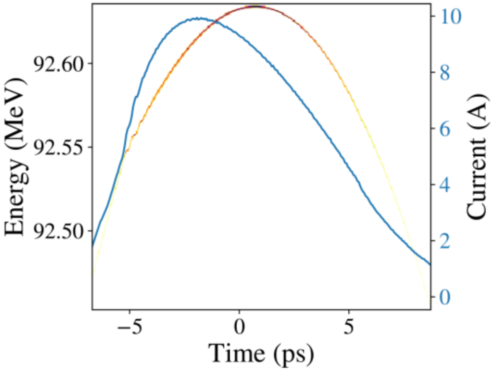


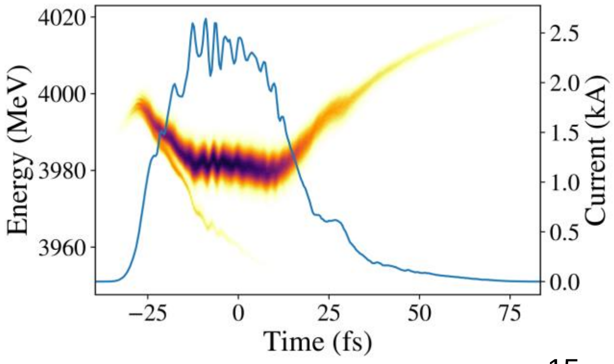




DCNS





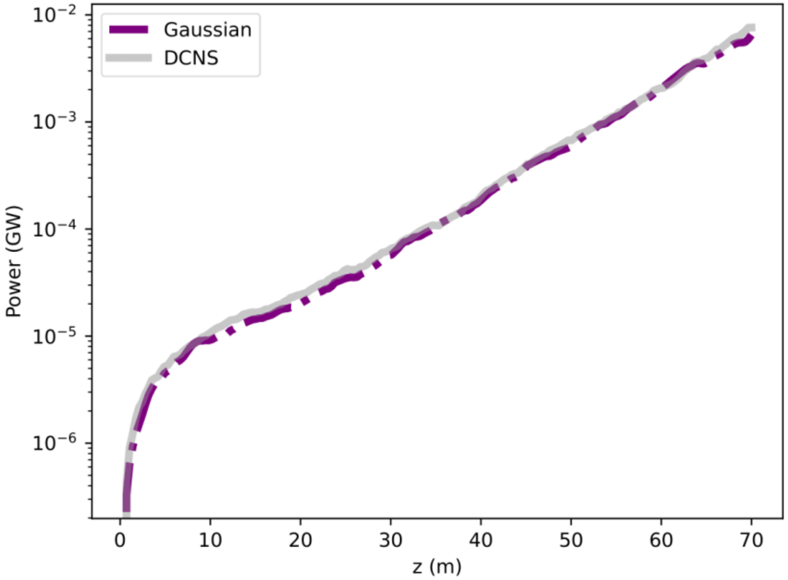


Neveu et al. “Nonlinearly Shaped Pulses in Photoinjectors and Free-Electron Lasers”, Under review at *Nuclear Inst. and Methods in Physics Research, A*

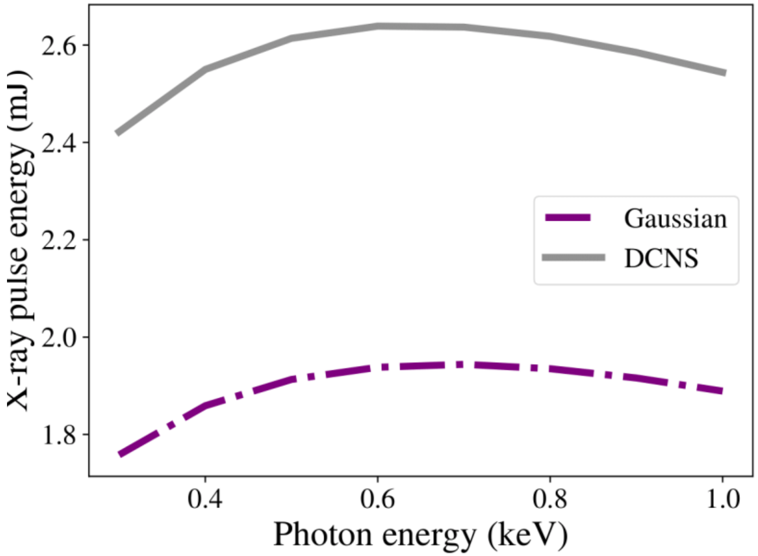
Theoretical FEL Performance

Ultimately the performance metric of interest is the x-ray beam parameters (e.g. power, energy, photon energy)

FEL power build up estimate along the undulators

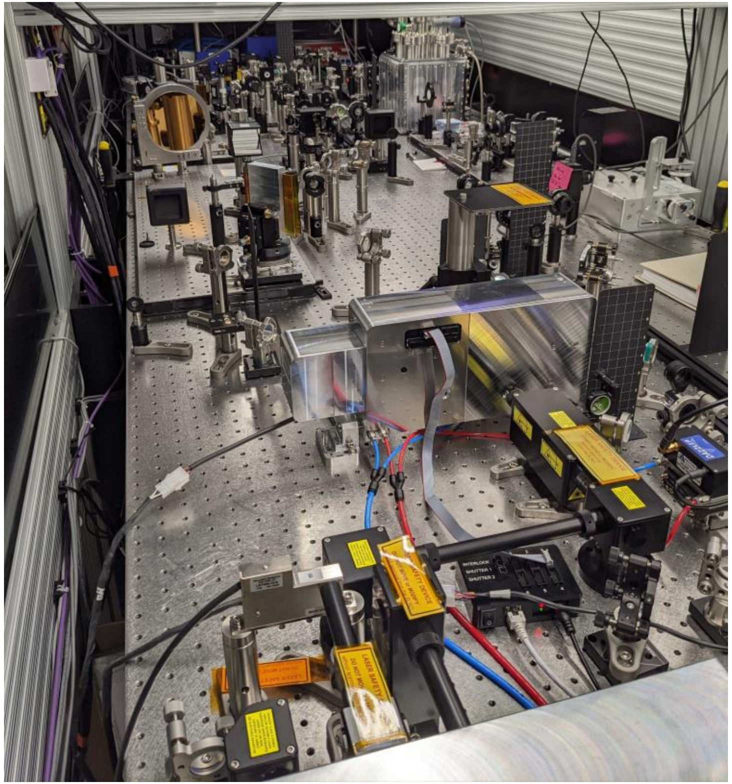


XFEL pulse energy per targeted photon energy



Neveu et al. “Nonlinearly Shaped Pulses in Photoinjectors and Free-Electron Lasers”, Under review at *Nuclear Inst. and Methods in Physics Research, A*

Experimental Demonstration



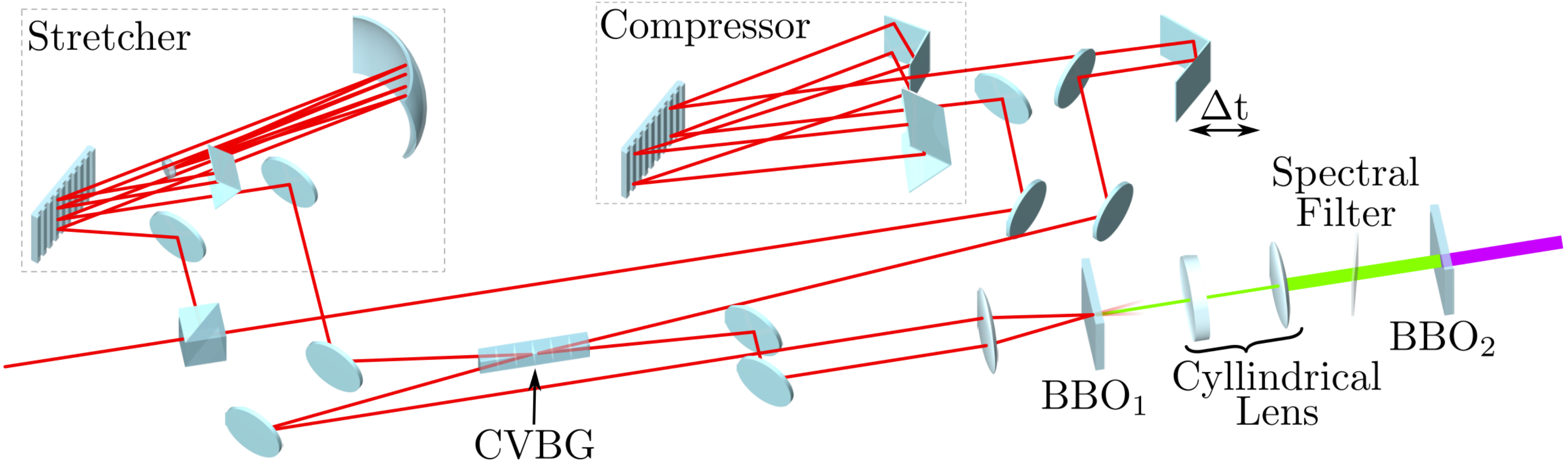
Required Laser Parameters

- Light Conversion Carbide
- 1024 nm, 246 fs, 40 W, 100 kHz – 1 MHz

Ideal Synthesized Pulse Parameters

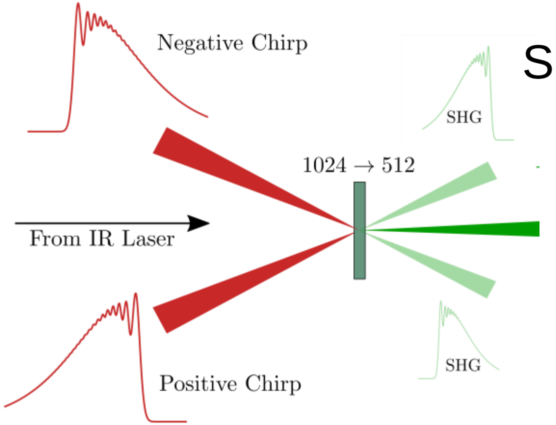
- 257.5 nm, 20-60 ps, >3 uJ across all rep rates
- Non-oscillatory and flattop temporal intensity profile

System Design



- 1024 nm, 246 fs, Gaussian → 256 nm, ~20 ps, Flattop
- 2.561 ps^2 SOD and 0.28 ps^3 TOD (α = 0.11 ps) on SFG inputs
- Frequency conversion and shaping integrated in monolithic design
- Capable of high average power and high pulse energy

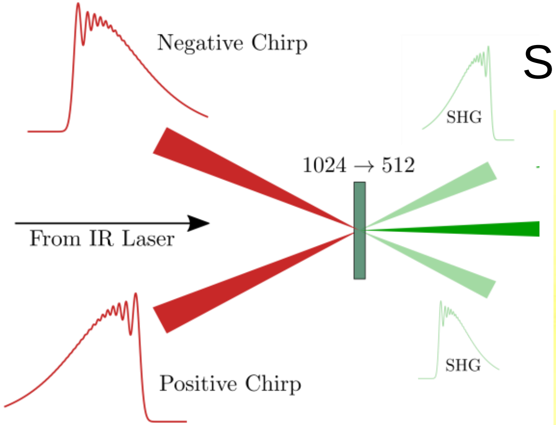
Sum Frequency Generation: Shaped 1024 → 512



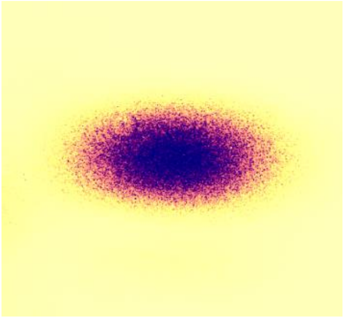
Spatial Distribution

- ~20 uJ of IR into SFG crystal
- ~6 uJ of Green in the SFG
- ~30% conversion efficiency
  - Conversion efficiency reduced when aligning for UV temporal profile

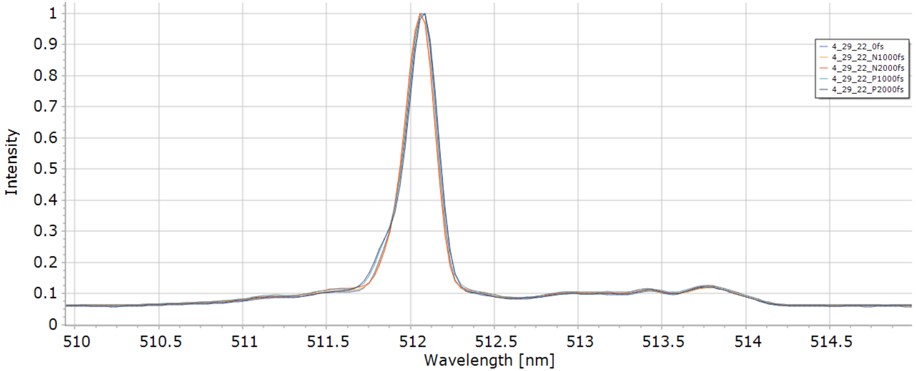
Sum Frequency Generation: Shaped 1024 ➔ 512



Spatial Distribution

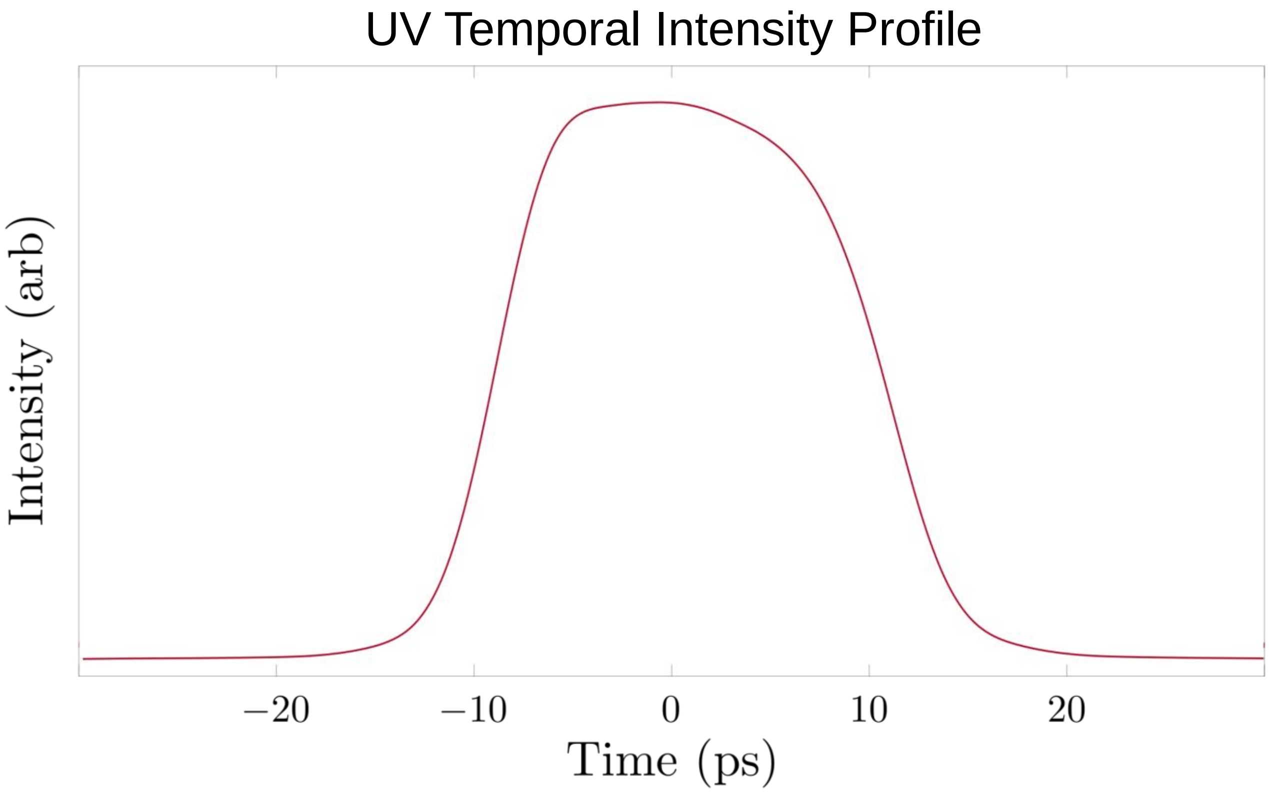


SFG + SHG Spectrum



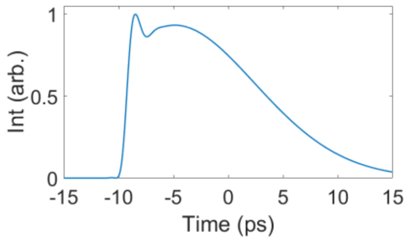
- ~20 uJ of IR into SFG crystal
- ~9 uJ of Green in the SFG
- ~30% conversion efficiency
  - Conversion efficiency reduced when aligning for UV temporal profile
- Gaussian spatial profile
  - Ellipticity due to oval cross section of crossed beams
- Variable SFG wavelength from 511 nm to 514 nm
- ~1-1.5 cm (33-50 ps) of overlap as determined by delay stage
- No direct time measurement due to device limitations

Smoothed UV Temporal Profile



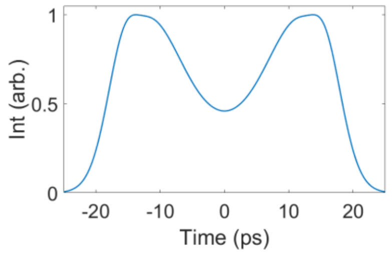
- IR & SFG filtered to reduced modulations on SFG and UV
- 19.8 ps FWHM duration
- Few ps rise and fall steepness
- Achievable at 250 kHz and 40 uJ of IR

Other Application of Phase-Only DCNS



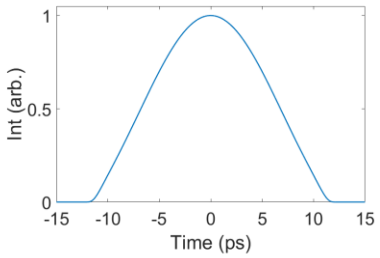
Plasma Wakefield Acceleration

- Increased accelerating gradients → Higher energy in same length
- 10 ps FWHM triangular pulse with sharp rising edge
- Initial pulse: 800 nm, 170 fs



Two-color/Dual-mode XFEL Lasing

- Time resolved x-ray pump probe experiments
- 40 ps FWHM pulse with sharp rise and falling edges and deep valley
- Initial pulse: 1550 nm, 70 fs

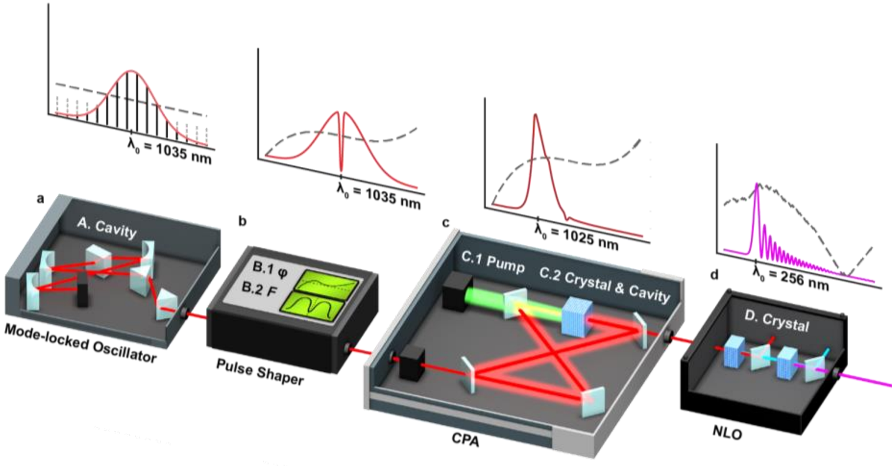


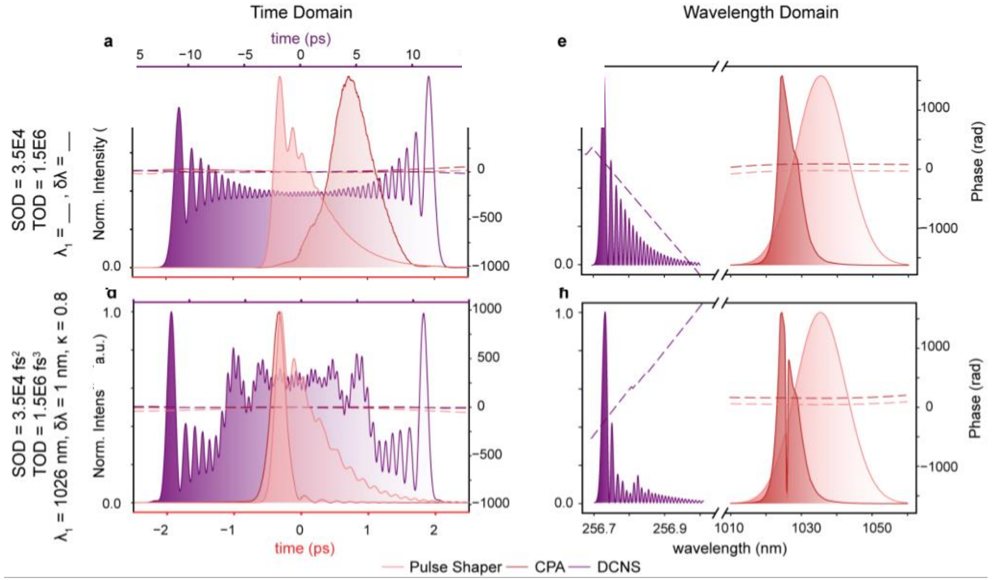
Electron Bunch Tail Mitigation

- Attosecond XFEL operation → Probe extremely transient phenomena
- 15 ps FWHM sawtooth pulse with constant rising/falling edge slopes
- Initial pulse: 1064 nm, 40 fs

Adaptive DCNS

Programable Extension to DCNS

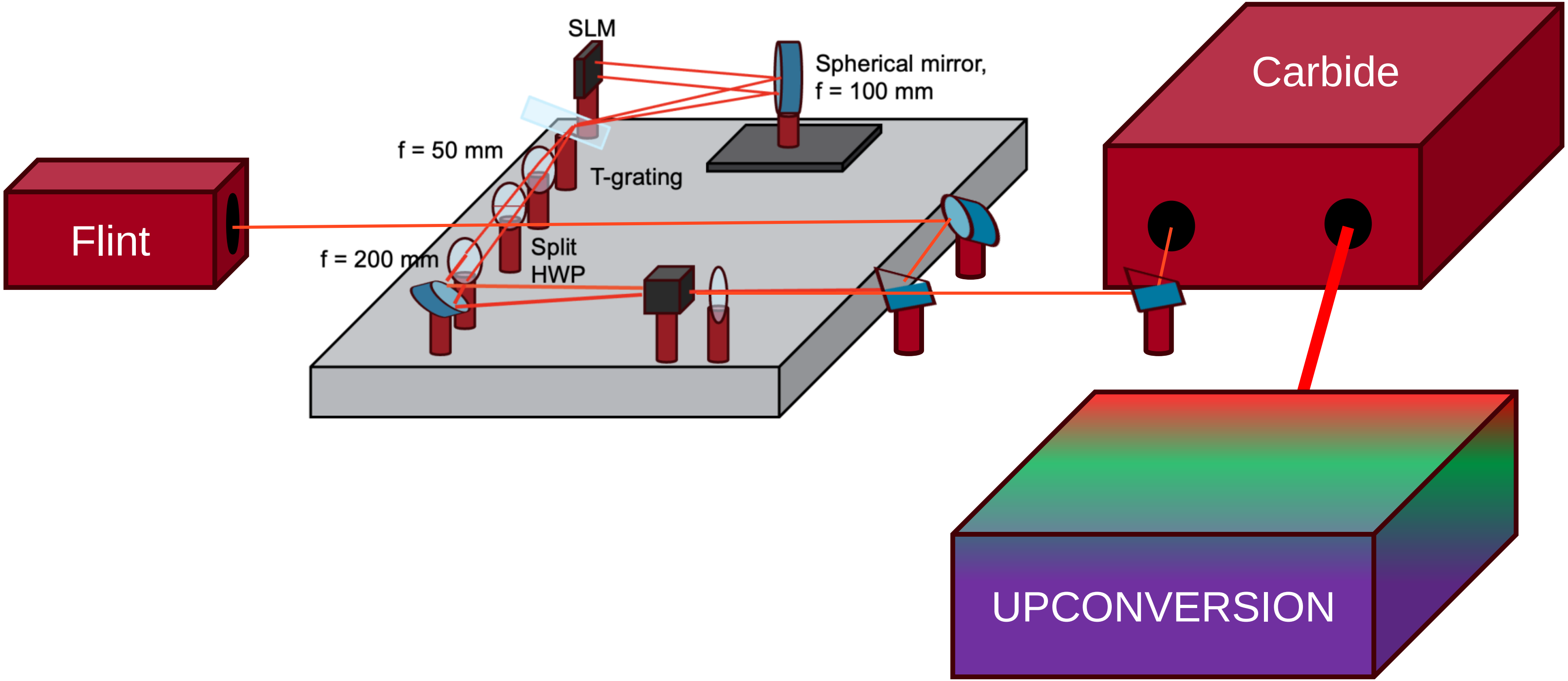




Hirschman, Jack et al. *Optics Express* 32.9 (2024)

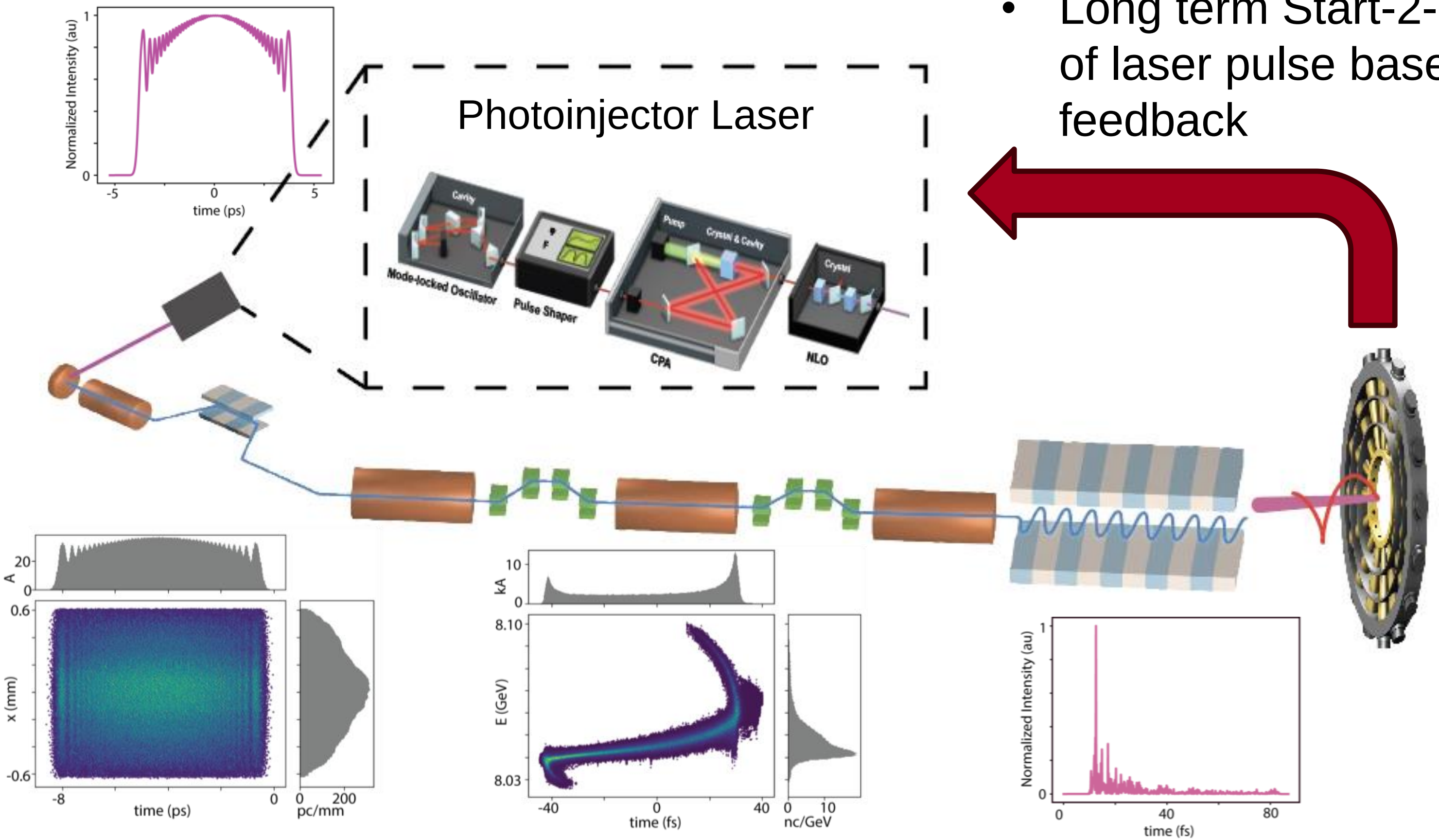
- Modify Oscillator Phase and Amplitude
- Preserve modifications through Amplifier
- On-the-fly optimization of UV pulse shape

SLM for Pre-Upconversion/Pre-Amplification Shaping



Pulse Shaping for End-to-End Optimization

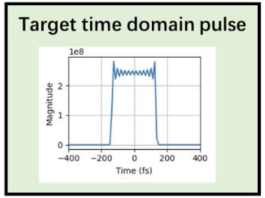
- Long term Start-2-End optimization of laser pulse based on XFEL feedback

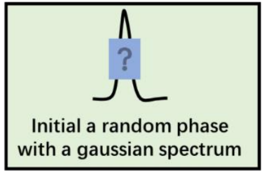


Beyond DCNS

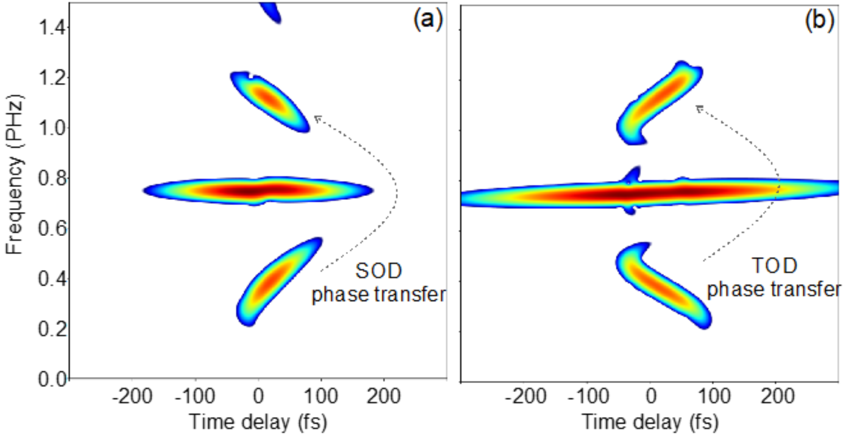
‘Smart’ IR Shaping for LCLS-II

- **(FY24-25)** Set up the HCF to demonstrate these shapes (flattop; perturbative UV) and characterization (Shape IR -> Shape UV)
- **(FY25-26)** Programmable shaping in the UV - also applicable to green photocathodes

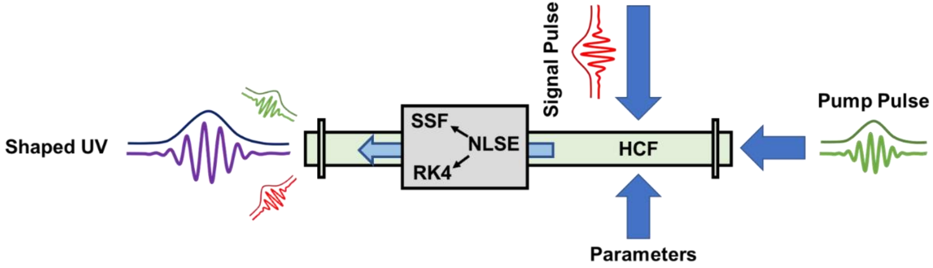




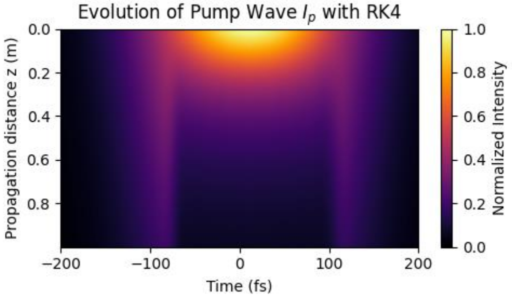
IFTA (Iterative Fourier Transform Algorithm)



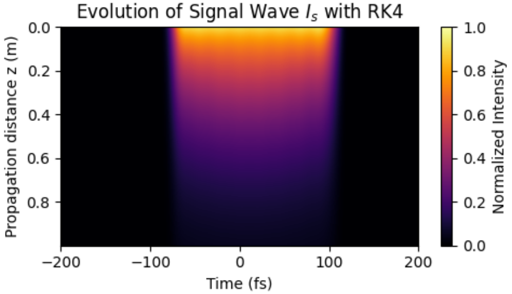
Hao Zhang, UCLA



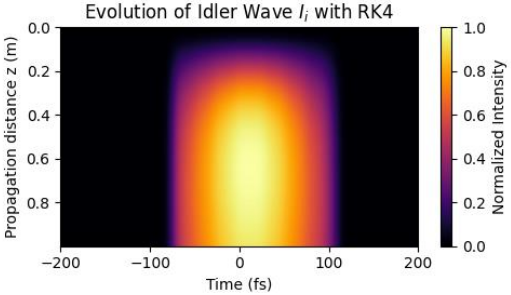
Green



IR



UV



Summary

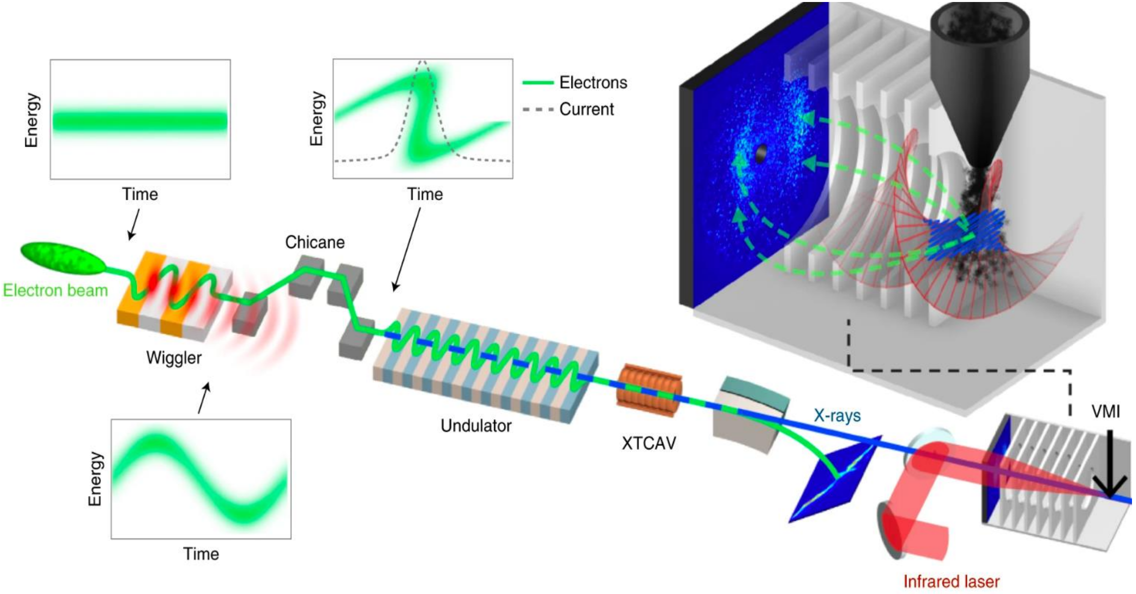
- Experimental verification of DCNS with a proof-of-principle system
  - ~20 ps smooth temporal flattop with quick rise and fall times as requested by LCLS-II operational requirements
  - Flattop DCNS shaping has potential for significant reduction in bunch tail effects of electron bunches produce in XFEL photoinjectors
  - Realistic approach towards high energy, high average power, photoinjector laser shaping system
- Adaptive shaping + DCNS provides and avenue toward dynamic optimization or modification of temporal intensity profiles
- FWM is an adaptive solution to the picosecond shaping problem across wavelengths and pulse durations

Thank you for your attention

Questions?

What is XLEAP

X-ray Laser-Enhanced Attosecond Pulse

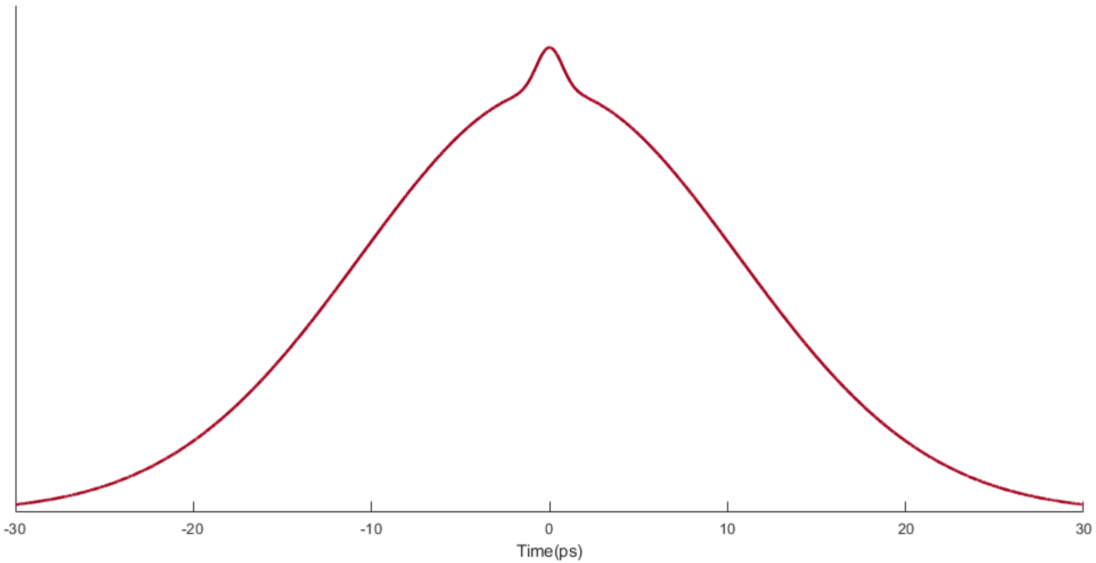


- Create a region in the e-beam with broad energy spread
- Compress this region to create a strong current spike
- Lase in the undulator on this energy broadened but short spike
- In NC we did this first with a Thulium laser but found the wiggler worked well enough by itself
- In SC we instead modulate the electrons in the Injector with a short UV beam

Original concept: *Zholents, PRSTAB 8, 040701 (2005)*
Duris, Nature Photonics 14.1 (2020): 30-36.
MacArthur, PRL 123.21 (2019): 214801.

Injector Modulation

Intensity Profile of Incident UV on SC Injector

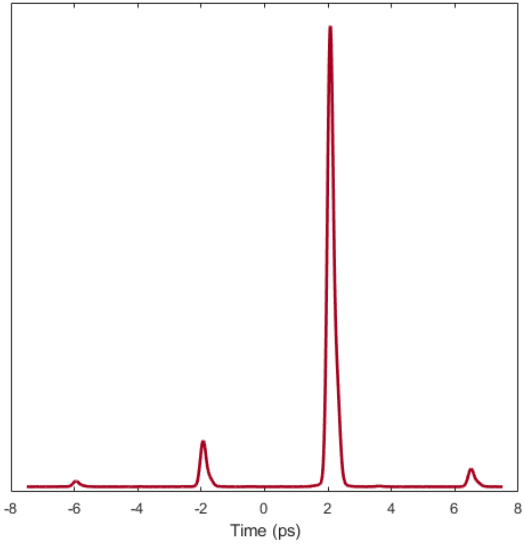


Short + Long Pulse UV

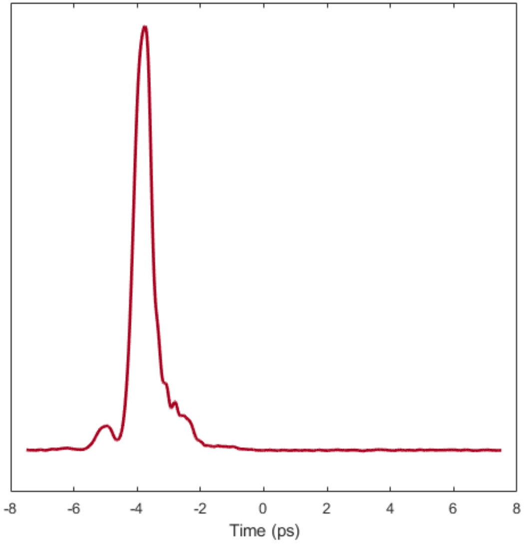
- Create small intensity spike on the standard Drive UV
  - This creates a current spike in the e-beam distribution that can be wigged and compressed
- Use Carbide at S0 to produce short (1.5 -3 ps) UV
- Stack on top of ~15ps Tangerine UV in the laser room
- Co-propagate through the spatial shaper (iris) and to the injector
- Independent control on time and intensity of short pulse

Carbide Short Pulse

No Extra Dispersion



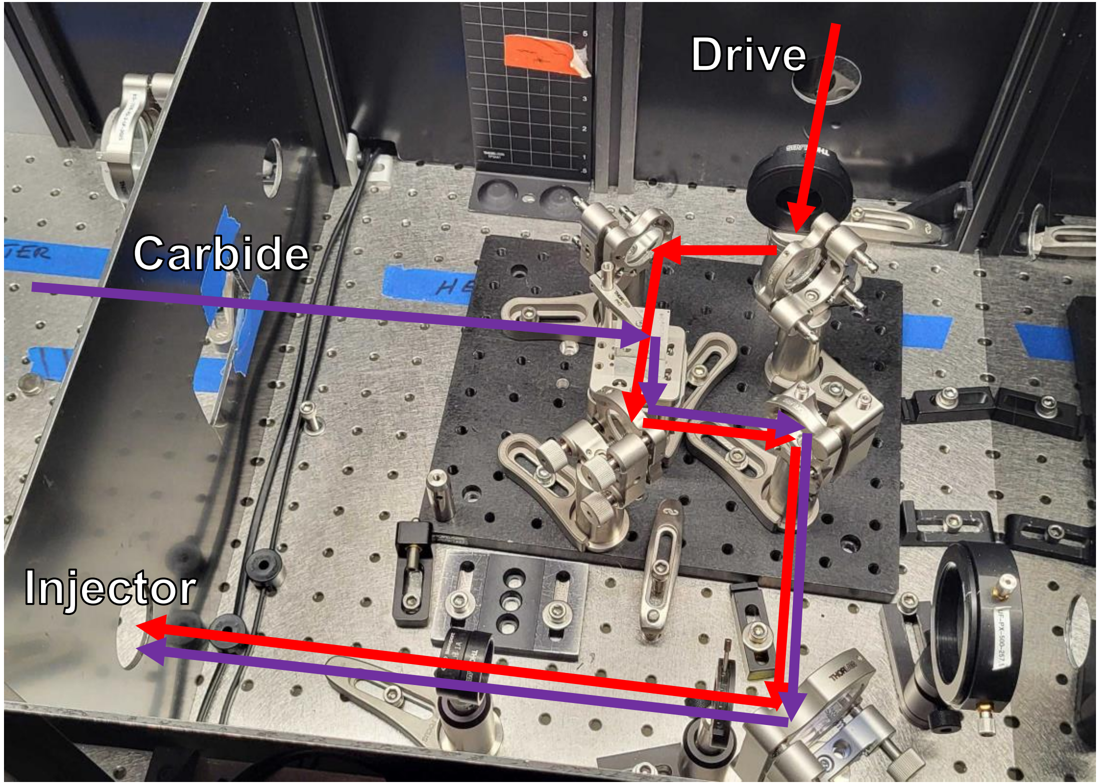
Proper Dispersion



UV Generation

- Regen running at 928 kHz, 43 uJ
  - Naturally comes out around ~250 fs
- 1024 →256 via 2-stage BBO SHG
- Stretching IR before conversion to get proper pulse duration
  - Internal compressor -10 ps – 10 ps
- Auto-Correlation measurement of UV duration
- No dispersion has ~150 fs UV pulses
  - Pre/post pulses from back reflections in a cube (taken out before running)
- Set internal compressor to ~4.5 ps to get 1.5 FWHM in UV

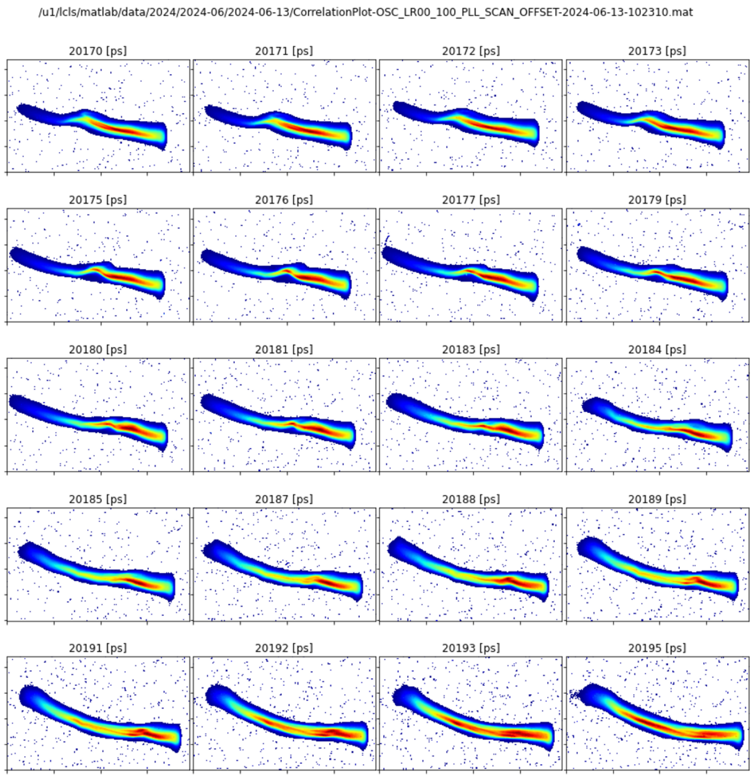
Carbide Overlap (Reality)



Spatial Stacking Board

- Spatial stacking in UV-grade PBS
  - Drive transmit, Carbide Reflect
- Stack in the laser room right before last mirror before ~30 transport tube to the Vault
- Had 1 iris and 1 camera in the laser room to align with
  - Added another iris later but still only a max of 2 ft before the tube
- 3 alignment cameras after the Transport tube
  - Tube only opens in NO ACCESS or Class 4 time during PAMM

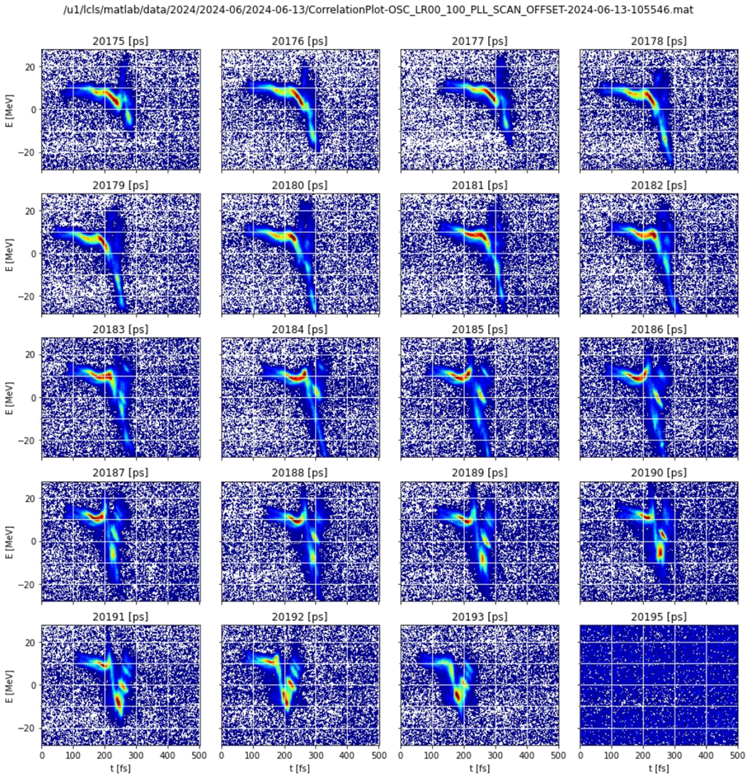
Temporal Overlap



Move Carbide to Tangerine

- All timing moves were done via the electronic controls on Carbide
- Rough timing (>15.4 ns) done by controlling 1) the window the AOM is open for and 2) which oscillator pulse the RA is picking
- Fine timing use primarily the scanning piezo's inside the Flint oscillator
  - Had ~1ps resolution over the full 15.4 ns separation between pulses
- No good diagnostics for timing in the laser room besides fast photodiodes
  - Could still get within range that scans of emitted charge with just Carbide could find few-ps level timing
- Final timing done by looking at e-beam profile just after the injector

Temporal Overlap



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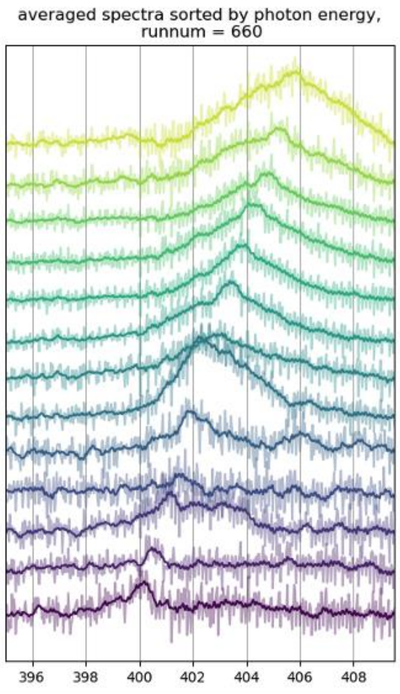
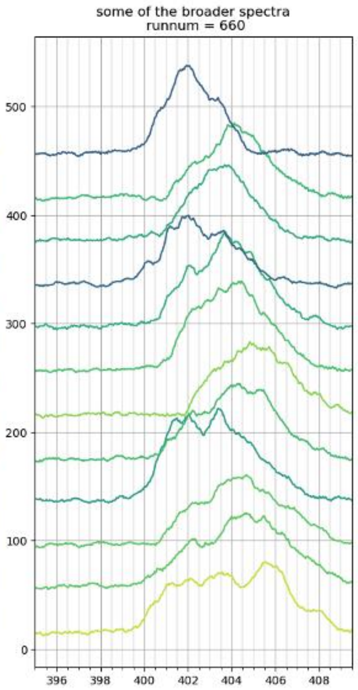
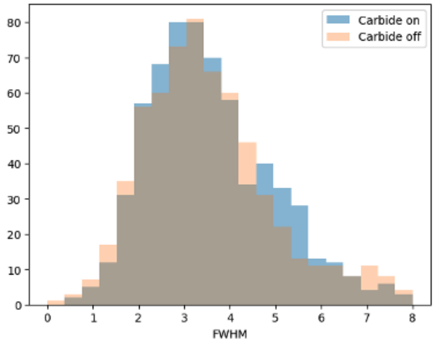
XLEAP Preliminary Results

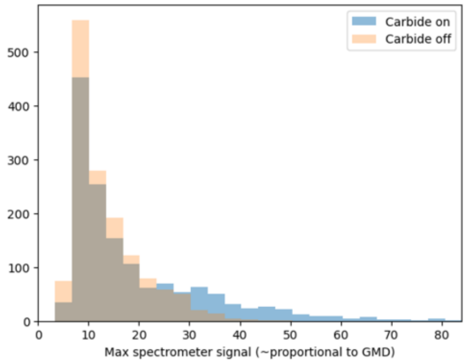
Carbide on ~66pC





- Tangerine provided a nominal 60 pC of charge, Carbide added 6 pC
- Greatest indication of XLEAP-like pulses is the broad and non-modulated x-ray spectrum
- While the FWHM of the XLEAP-like pulses doesn’t have a strong increase when Carbide is present, the peak intensities can be significantly higher





Thank you (Again ☺) for your attention

Questions?