Pulse characterisation techniques for multi-pulse laser plasma wakefield accelerators

Speaker: Warren Wang

Position: 4th year PhD student

Supervisors: Simon Hooker and Roman Walczak

Institute: University of Oxford

John Adams Institute for Accelerator Science

UNIVERSITY OF OXFORD

Outline

- Introduction
    - Conventional accelerators versus laser-driven plasma wakefield accelerators
    - Why pulse trains?
- Concepts of plasma accelerators driven by laser pulse trains
    - Multi-pulse laser plasma wakefield accelerators
    - Plasma-modulated plasma accelerators
    - Pulse train generation techniques
- Pulse characterization techniques
    - Representation of short pulses and pulse trains
    - Overview of characterisation techniques
    - FROG and SEA-TADPOLE
- Implementation of pulse characterization techniques
    - Development of FROG for MP-LWFA
    - Development of FROG + SEA-TADPOLE for P-MoPA
- Conclusion

Conventional accelerators versus laser-driven plasma wakefield accelerators

Pulsed RF power ← Klystron

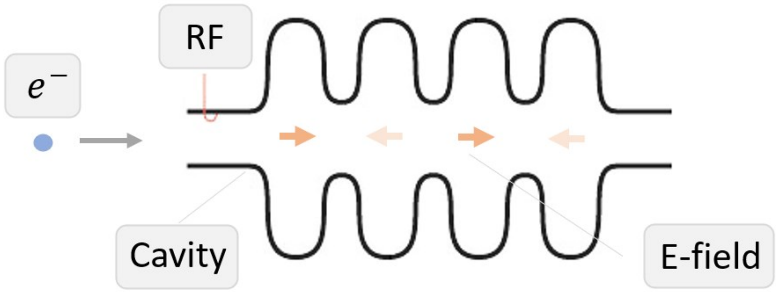
↓

Cavity → Longitudinal E-field → Acceleration

↑

Particle source

$\frac{dV}{dx} \sim$ 0.1 GV/m



Ultra-short pulse ← Ti-Sapphire laser

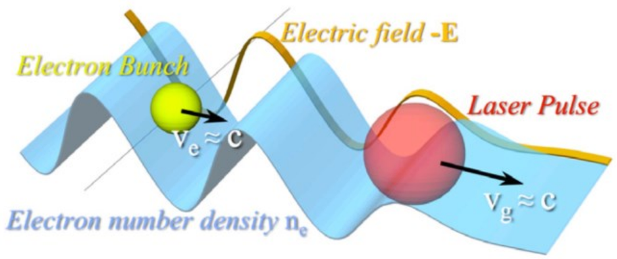
↓

Plasma → Longitudinal E-field → Acceleration

↑

Particle source

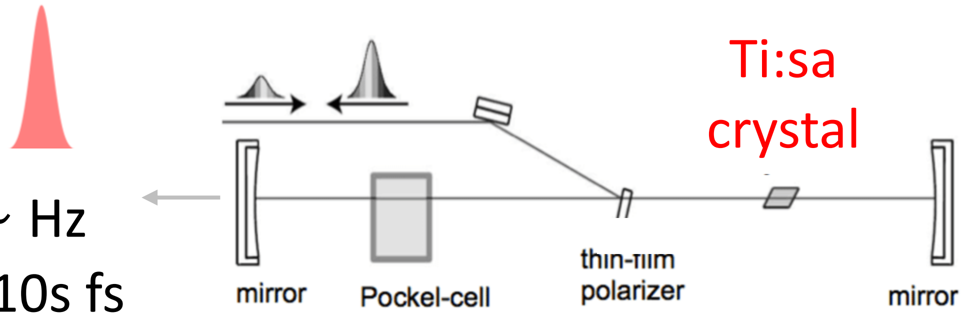
$\frac{dV}{dx} \sim$ 100 GV/m



F Albert et al., Plasma Phys. Control. Fusion 56 (2014).

Why pulse trains?

Inefficient laser systems ($QD \sim 35\%$)

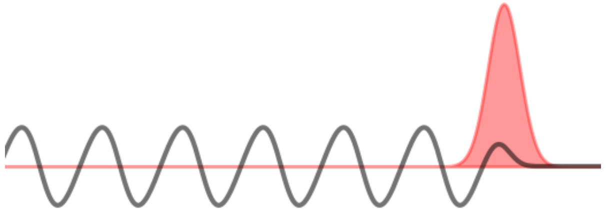


Ti:sa crystal

$\sim$ Hz

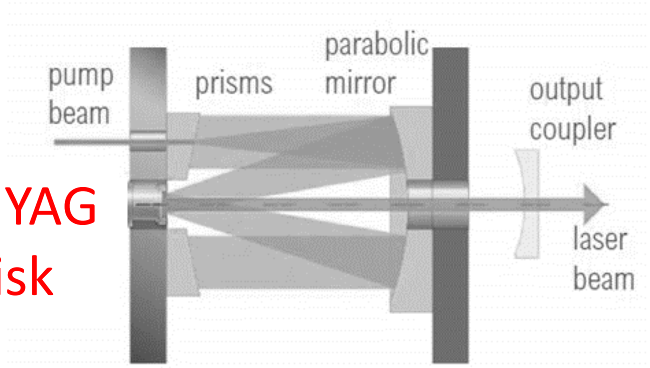
$\sim$ 10s fs

Conventional LWFA



Efficient laser systems ($QD \sim 9\%$)

Yb:YAG disk

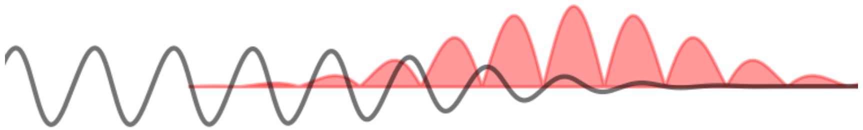


$\sim$ 1k Hz

$\sim$ 1 ps

Train of pulses

Pulse spacing $\sim$200 fs (Resonance excitation)



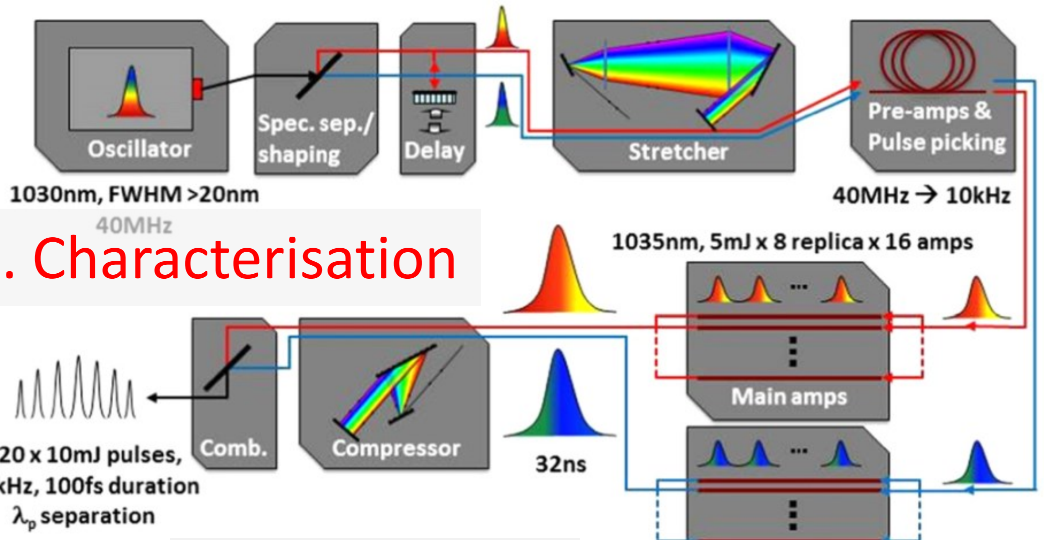
Wakefields Laser pulse

Multi-pulse LWFA (MP-LWFA)

1. Fibre laser

2. Shaping

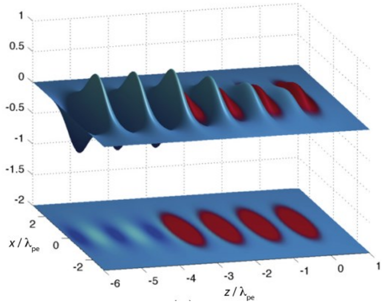
3. Pulse picking



6. Characterisation

5. Compression

4. Amplification

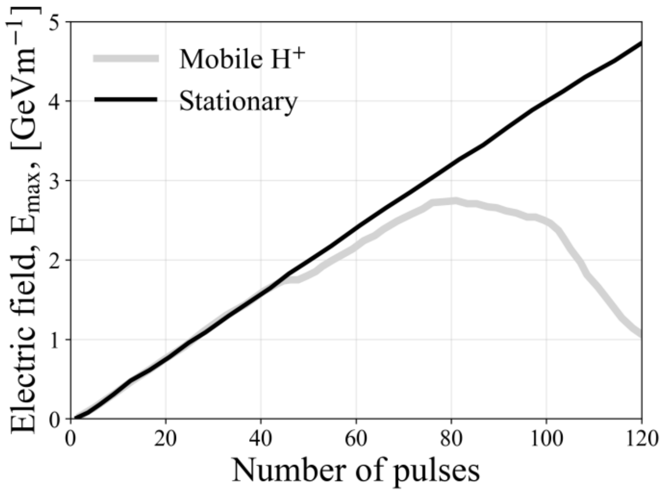


7. Excitation

Simulation: 2D PIC

Pulse energy: 10 mJ

Pulse duration: 100 fs



80 low energy short pulses

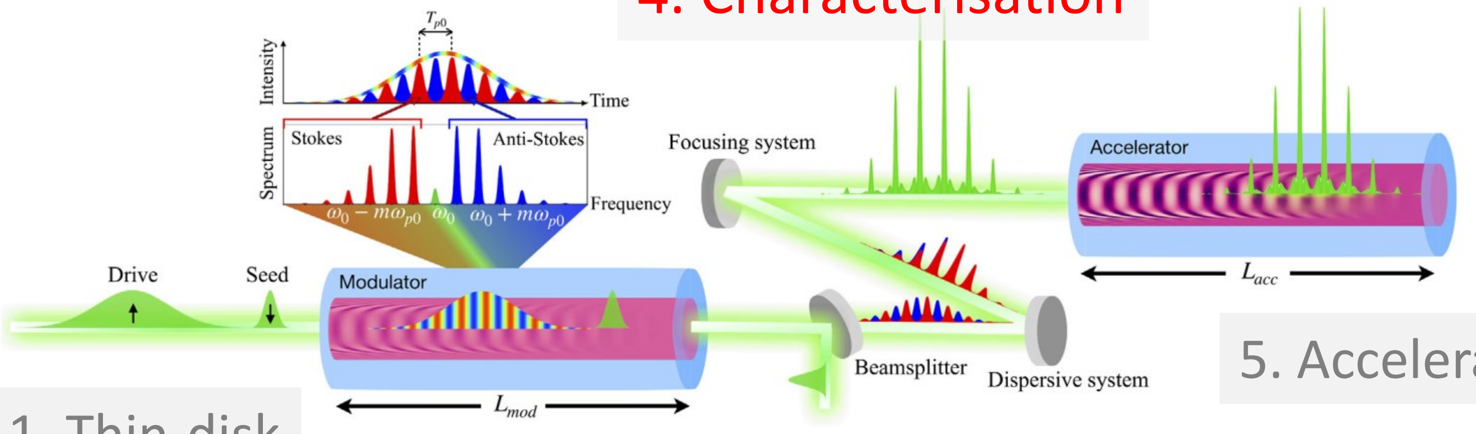
Achieve 3 GV/m!

Simon Hooker et al., J. Phys. B: At. Mol. Opt. Phys. 47 (2014).

Plasma-modulated plasma accelerators (P-MoPA)

Simulation: 2D PIC
Pulse energy: 600 mJ
Pulse duration: 1 ps

4. Characterisation

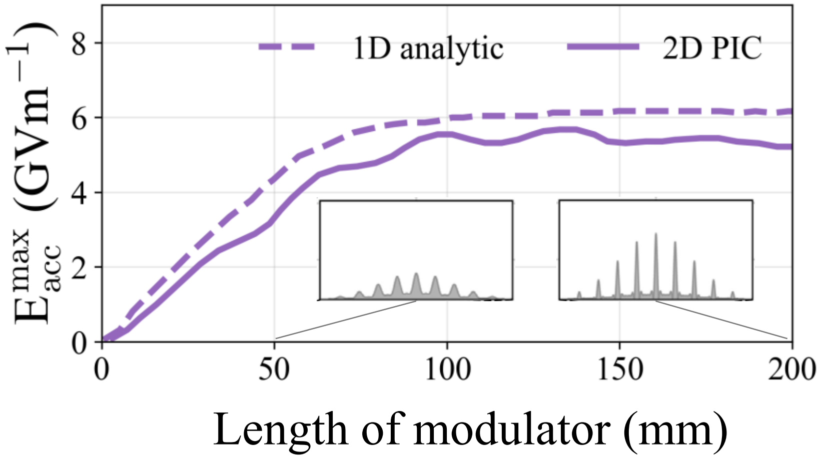


1. Thin-disk Laser

2. Modulation

3. Compression

5. Acceleration



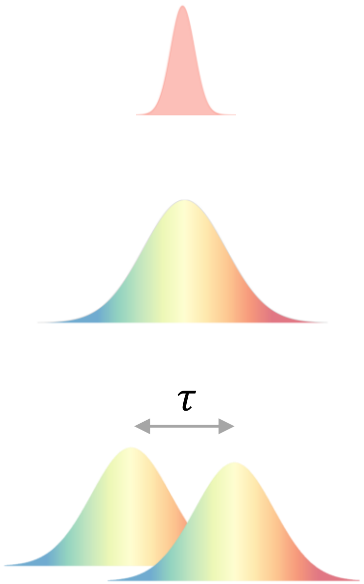
Oscar. Jakobsson et al., Physical Review Letters 127, 184801 (2021).

Single long pulse
(9 short pulses)
Achieves 6 GV/m !

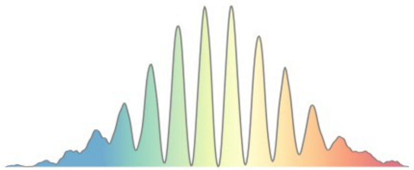
Pulse train generation techniques

MP-LWFA concept

Broadband	Single short pulse
+	
Pulse stretching	Grating pair compressor
+	
Delay time control	Michelson interferometer

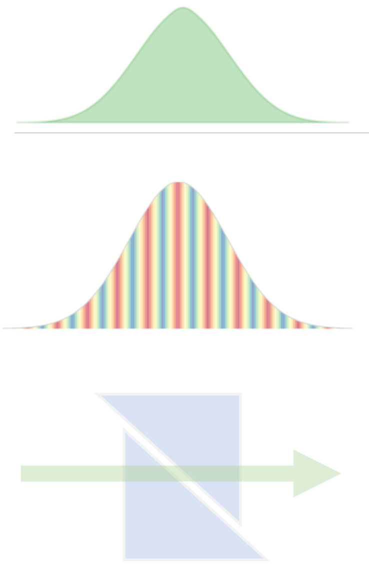


=

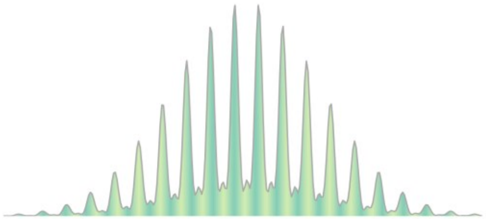


P-MoPA concept

Narrow band	Single long pulse
+	
Phase modulation	Plasma wakefield
+	
Dispersion Control	Dispersive optics



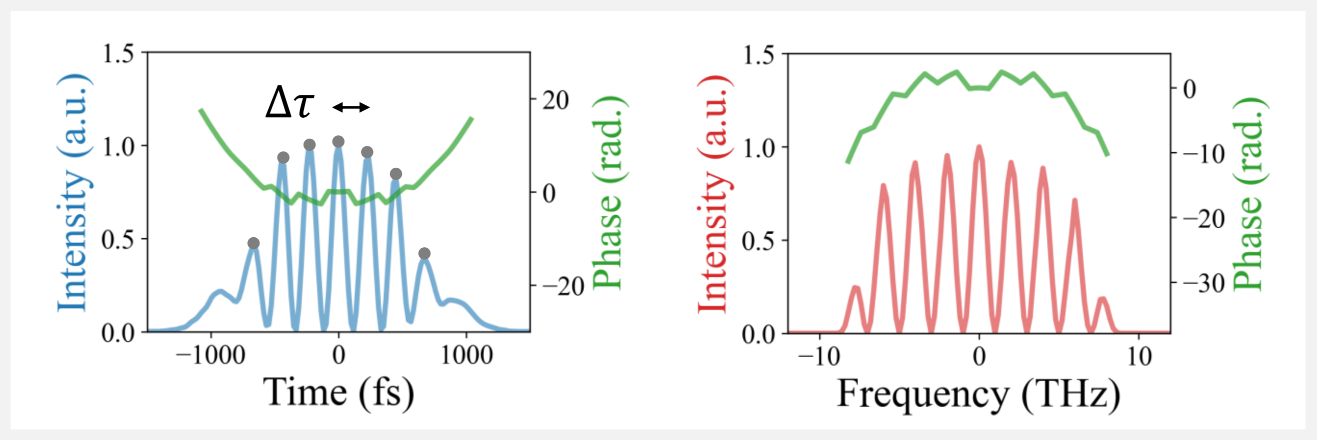
=



Structure of pulse trains

Time domain | Frequency domain

MP-LWFA

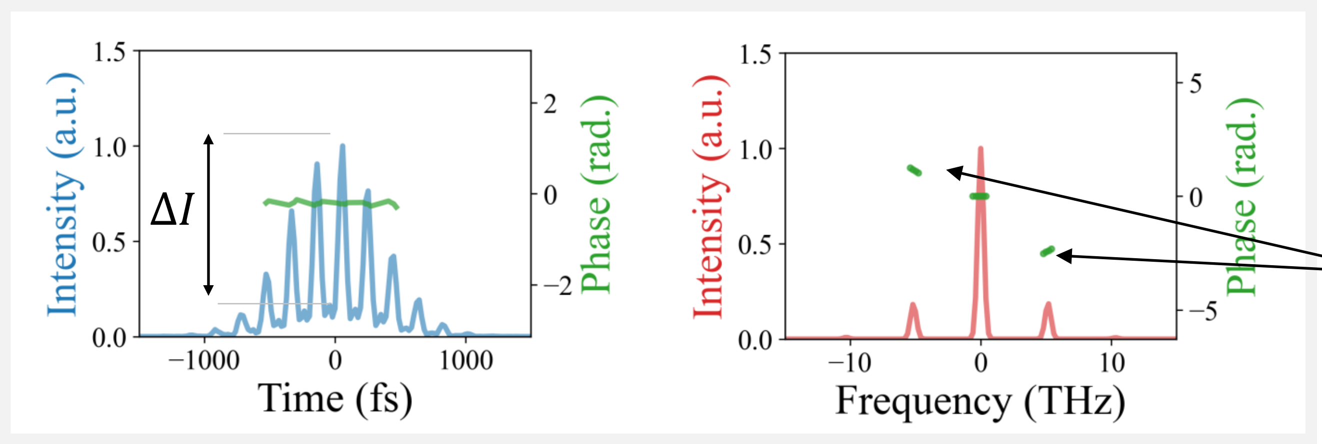


Pulse spacing: $\Delta\tau$

Number of pulses:

Oscillating spectrum

P-MOPA



Pulse contrast: ΔI

Spectral phase:

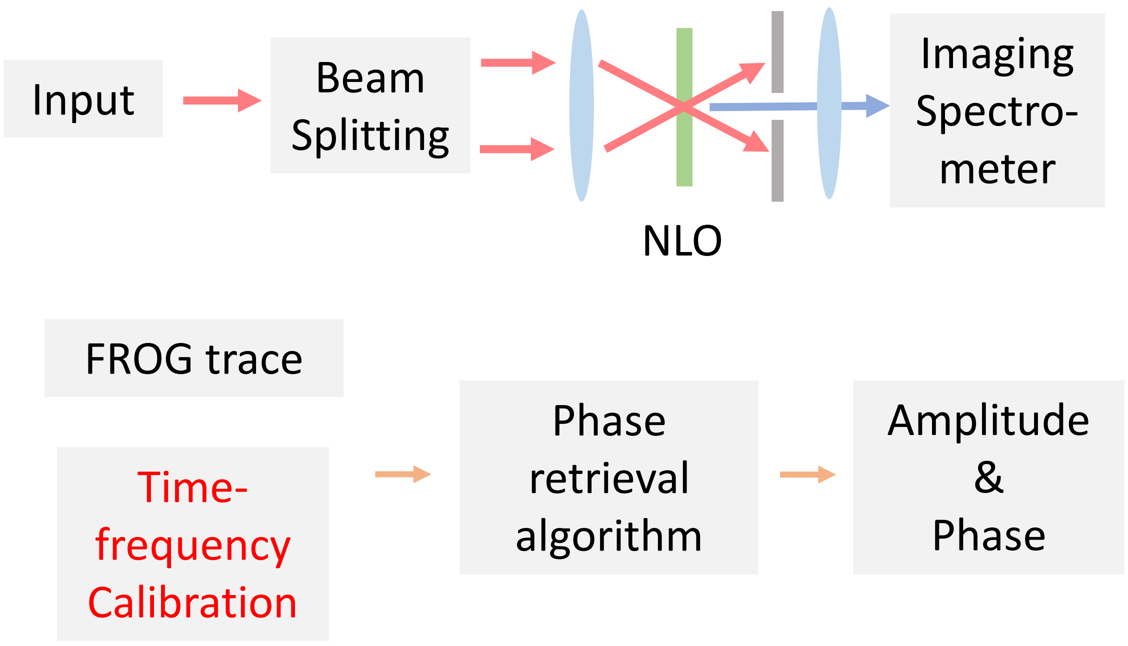
Phase jumps

Pulse characterisation techniques

	Techniques	Measured signal	Measured phase
Time-frequency correlation	Frequency-resolved optical gating (FROG)	Self-referenced Spectrogram $I(\tau, \omega)$	$\psi(\omega) = \sum_{n=2}^{\infty} \frac{1}{n!} \frac{\partial^n \psi(\omega)}{\partial \omega^n} \omega^n$
	Cross-correlation frequency-resolved optical gating (XFROG)	Cross-referenced Spectrogram $I(\tau, \omega)$	$\psi(\omega) = \sum_{n=2}^{\infty} \frac{1}{n!} \frac{\partial^n \psi(\omega)}{\partial \omega^n} \omega^n$
Spectral intereferometry	Spatial Encoded Arrangement for Temporal Analysis by Dispersing a Pair of Light E-fields (SEA-TADPOLE)	Cross-referenced Interferogram $I(\omega, x)$	$\Delta\psi(\omega) = \psi_t(\omega) - \psi_r(\omega)$
	Spectral phase interferometry for direct electric-field reconstruction (SPIDER)	Self-referenced Interferogram $I(\omega)$	$\frac{\partial \psi}{\partial \omega} = \frac{\psi(\omega - \Omega) - \psi(\omega)}{\Omega}$

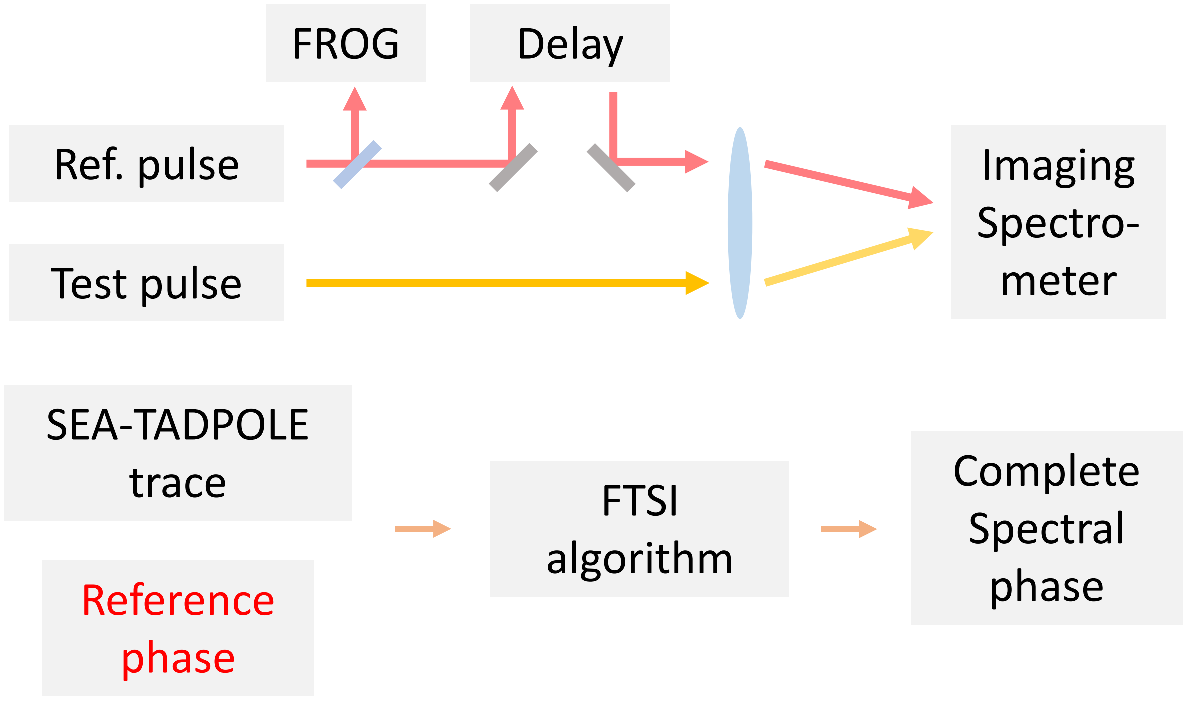
FROG and SEA-TADPOLE

FROG



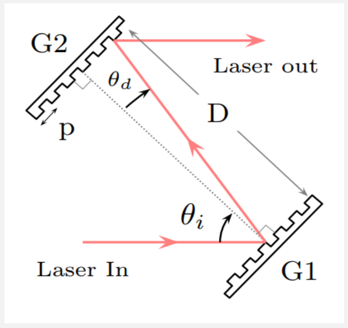
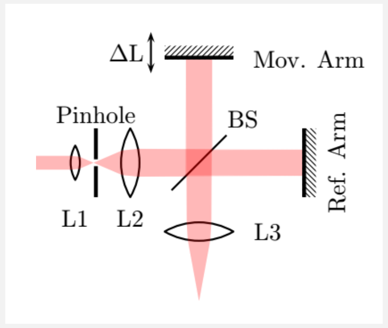
Rick Trebino et al., J. Opt. Soc. Am. A, Vol. 10, No. 5 (1993).
Spangenberg et al., Physical Review A 91, 021803(R) (2015).

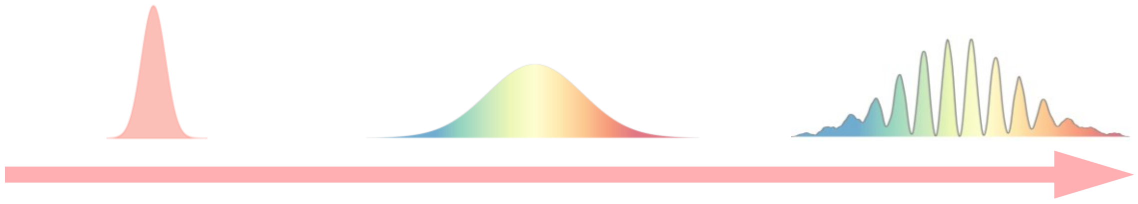
SEA-TADPOLE



Pamela Bowlan et al., Optics Express, Vol. 14, No. 24 (2006).

Pulse characterization technique for MP-LWFA

Ti-Sapphire Laser system	Grating pair Compressor	Michelson Interferometer
2 mJ, 50 fs, at 790 nm, at 1 kHz		



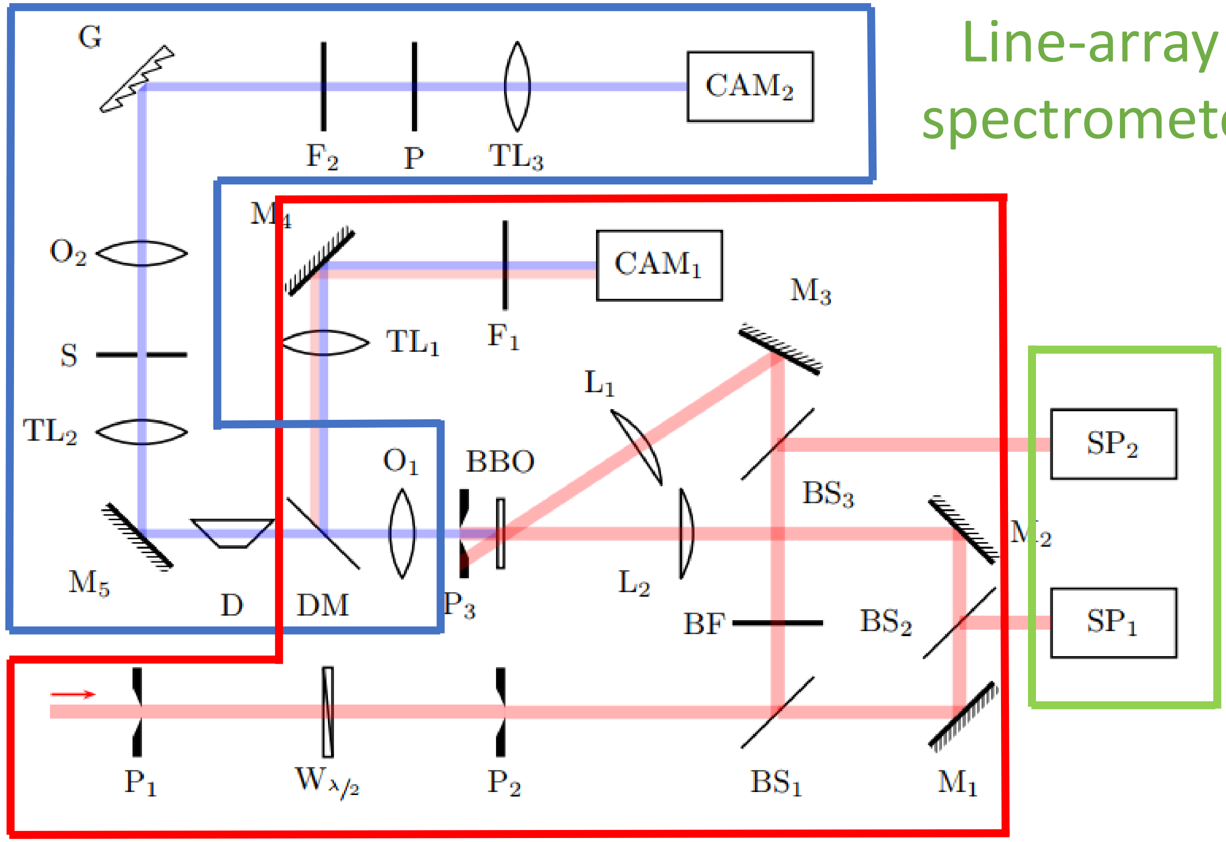
Broadband Short pulse

Stretching

Temporal interference

High res. imaging spectrometer

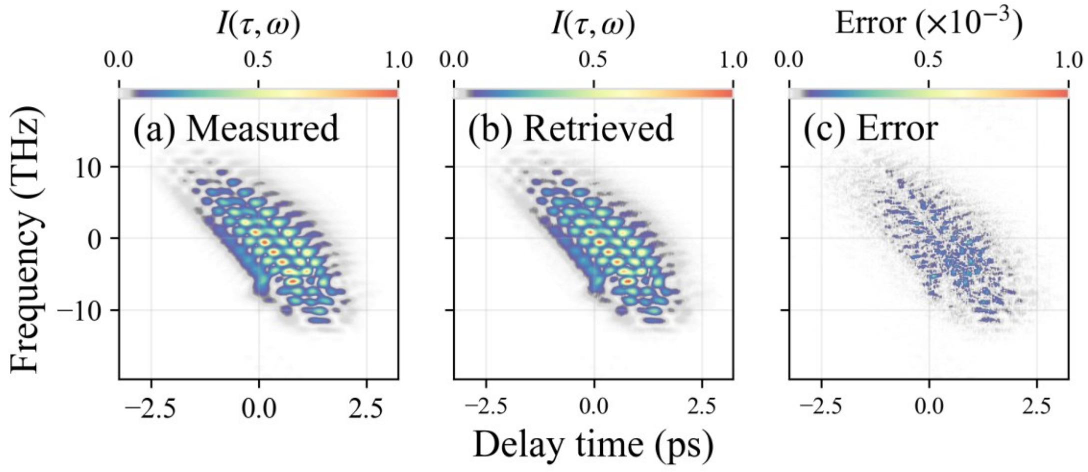
Line-array spectrometer



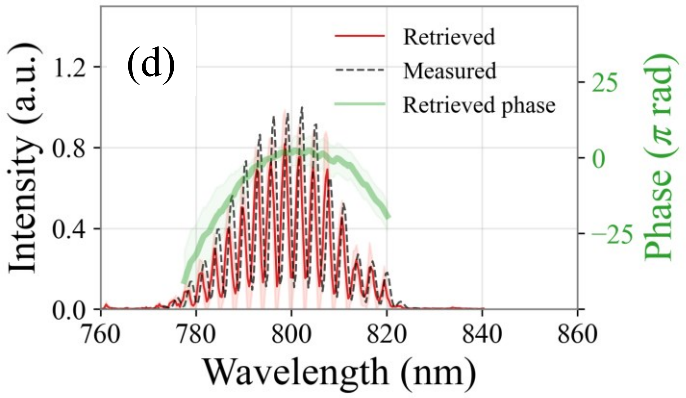
Self-referenced cross-correlator

Experimental pulse retrieval results

FROG Trace

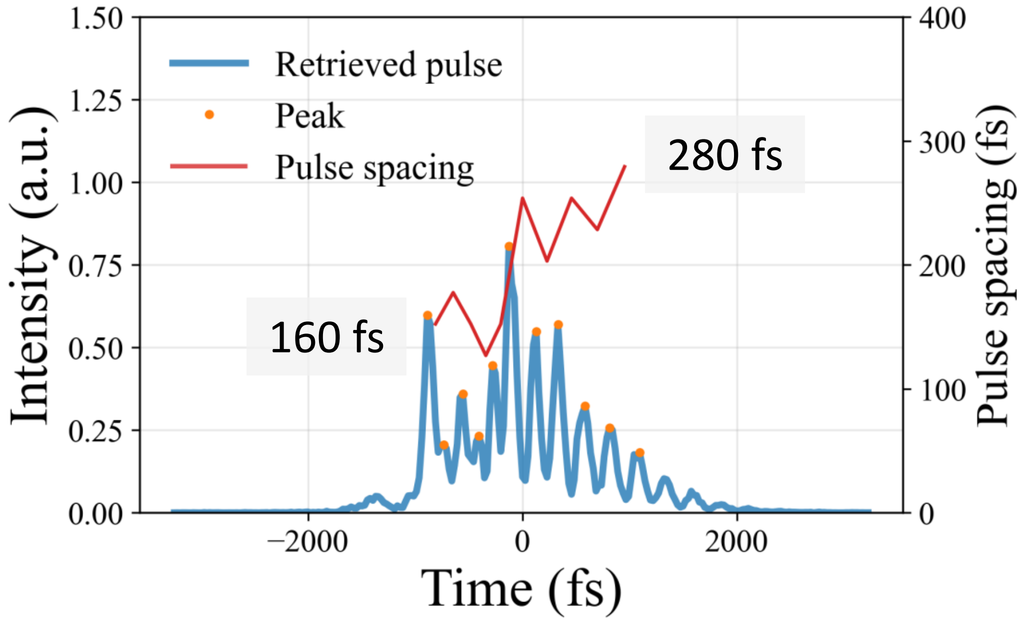


Spectrum



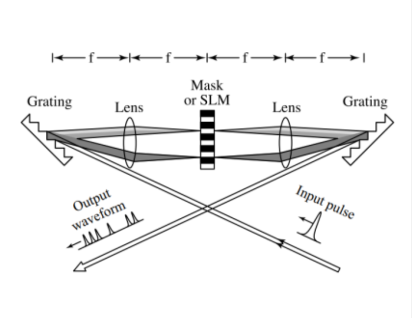
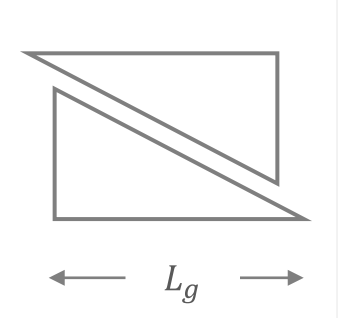
FROG Error: 9×10^{-3}
RMS Intensity error: 14 %

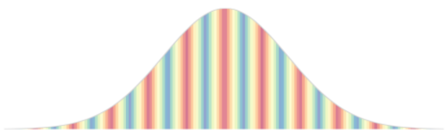
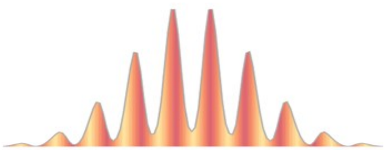
Pulse structure



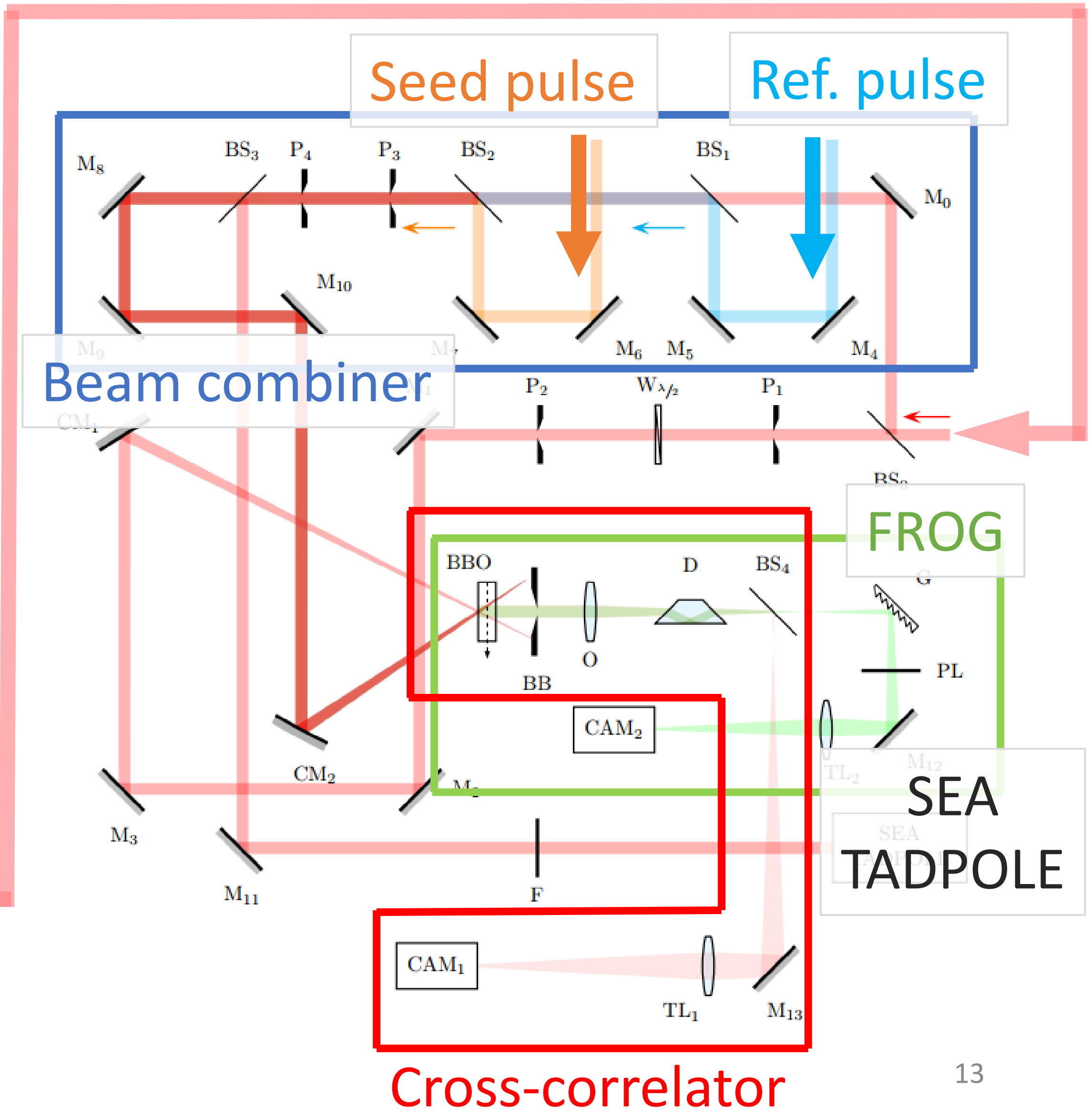
- Number of pulses: ~ 11
- Time bandwidth product: ~ 13
- Avg. pulse spacing: ~200 fs
- Non-uniformity detected.

Pulse characterisation technique for P-MoPA

Ti-Sapphire Laser system	4-f pulse shaper	Prism pair Compressor
2 mJ, 50 fs, at 790 nm, at 1 kHz		

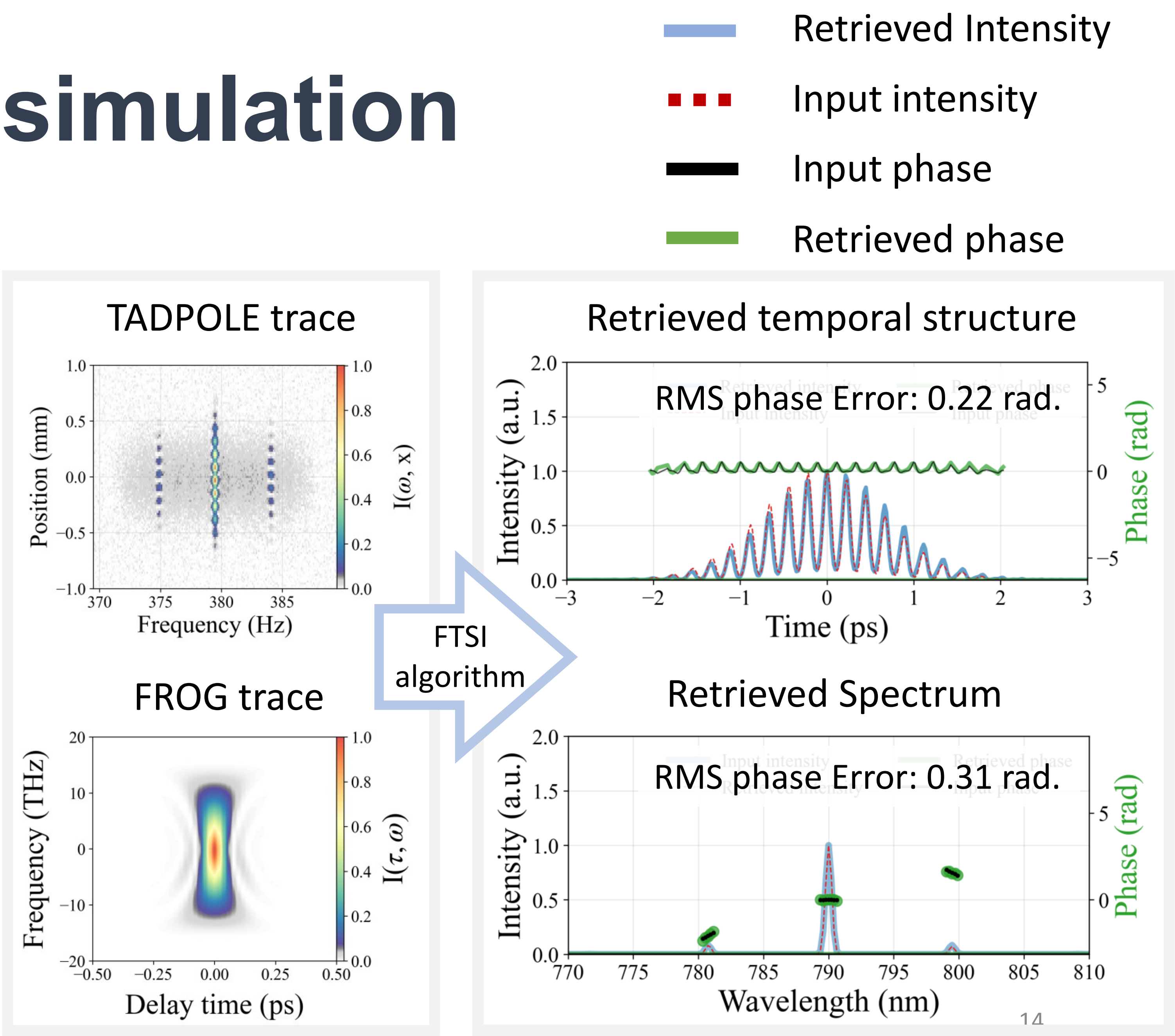
Broadband Short pulse	Spectral masking Phase modulation	Pulse Compression



Pulse retrieval simulation

Simulation conditions

- Plasma density n: 2.5e17 cm^{-3}
- Plasma modulation $\delta n/n$: 2%
- Channel length L_c : 5 cm
- Glass length L_g : 8 cm
- Centre wavelength of pulse λ_0 : 790 nm
- Seed pulse duration: 50 fs
- Drive pulse duration: 1.4 ps
- Spectral SNR : 20 dB (white noise)
- Sensor SNR: 43 dB (Gaussian noise)
- Uncertainty of gas density: 5 %
- RMS Timing jitter: 200 fs



Conclusion

- LWFA driven by pulse trains allows use of new laser technology with high rep. rates (kHz) and high wall-plug efficiency (>16%).
- Pulse characterisation is crucial for pulse train optimisation in MP-LWFA/P-MoPA.
- Multi-pulse trains can be diagnosed by FROG. Entire temporal structure of pulse trains can be retrieved.
- Characterisation of plasma modulated pulse trains require FROG and spectral interferometry (SEA-TADPOLE). Complete intensity and phase can be retrieved with smooth reference phase.

Back-up slides

Representation of ultra-short pulses

Spectrum + Spectral phase —iFT→ Temporal structure

(Time-frequency relation)

Flat | Quadratic | Cubic | Jumps

Frequency domain

↓ iFT

Time domain