Attosecond Pulse Generation with Synthesized Sub-Cycle Laser Pulses

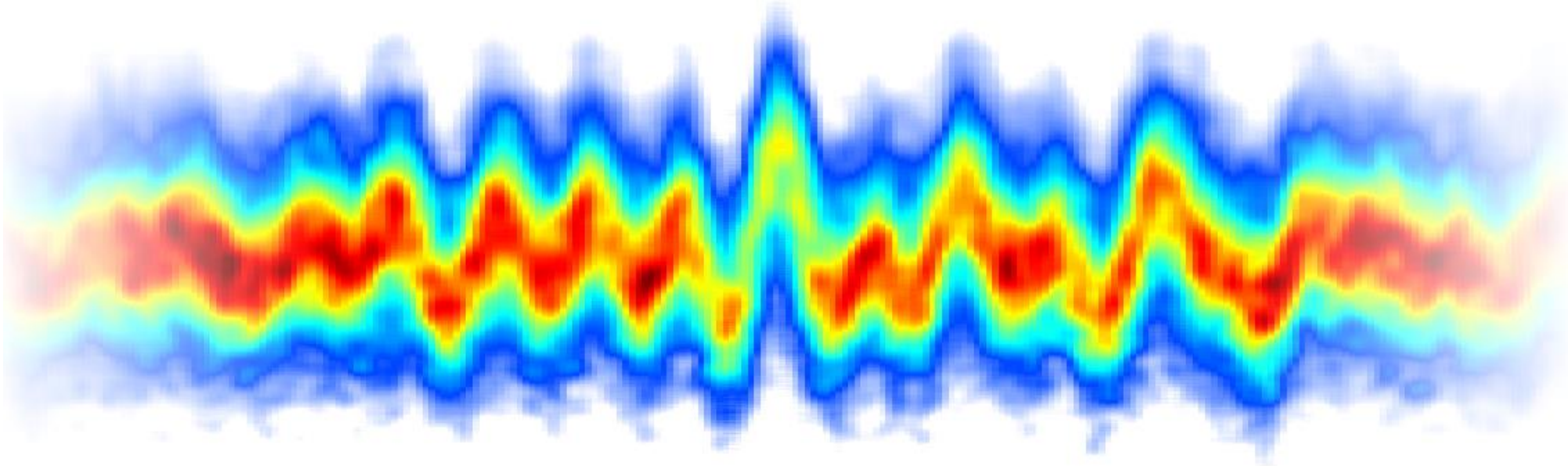
Roland E. Mainz, Giulio Maria Rossi, Fabian Scheiba, Miguel A. Silva-Toledo,
Maximilian Kubullek, Yudong Yang, and Franz X. Kärtner

Detector Workshop

Hamburg, Germany

Talk: Thu 15:05

1st June 2023



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CFEL SCIENCE

DESY

UH

CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

Group of Ultrafast Optics and X-Rays

At CFEL, Group of Prof. Franz X. Kärtner

Center for Free-Electron Laser Science

Our Team

Group Leader

Prof. Franz X. Kärtner

Synthesizer and Attoscience Team Members

Dr. Roland E. Mainz

Dr. Fabian Scheiba

Alumni

Dr. Giovanni Cirmi

Team Leader

Dr. Giulio Maria Rossi

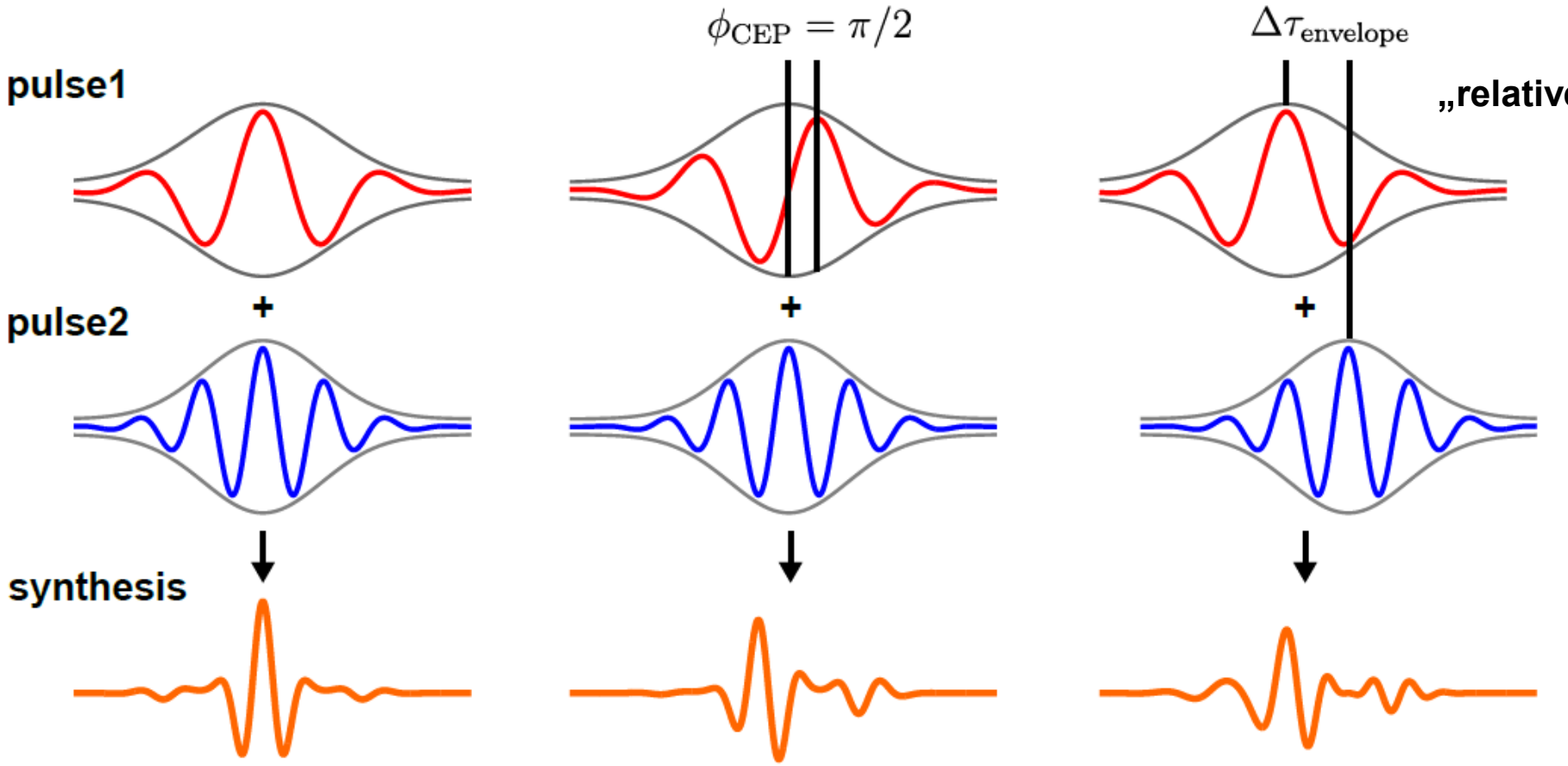
Miguel Angel Silva-Toledo

Maximilian Kubullek

Dr. Yudong Yang

The Synthesis of Few-Cycle Laser Pulses

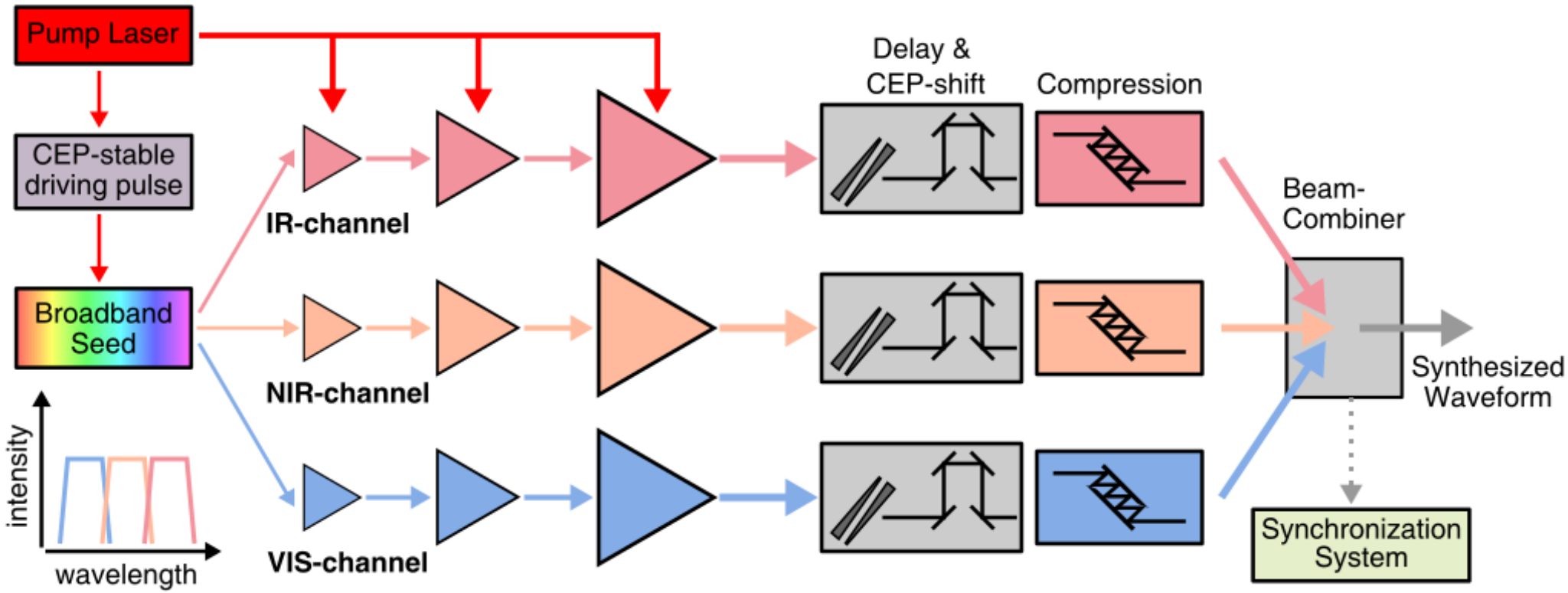
Crafting laser pulses shorter than one optical cycle



Review-Article on Synthesis:
G. Cirmi et al., LPR 2200588 (2023)

Synthesizer Scheme based on Optical Parametric Amplifiers (OPAs)

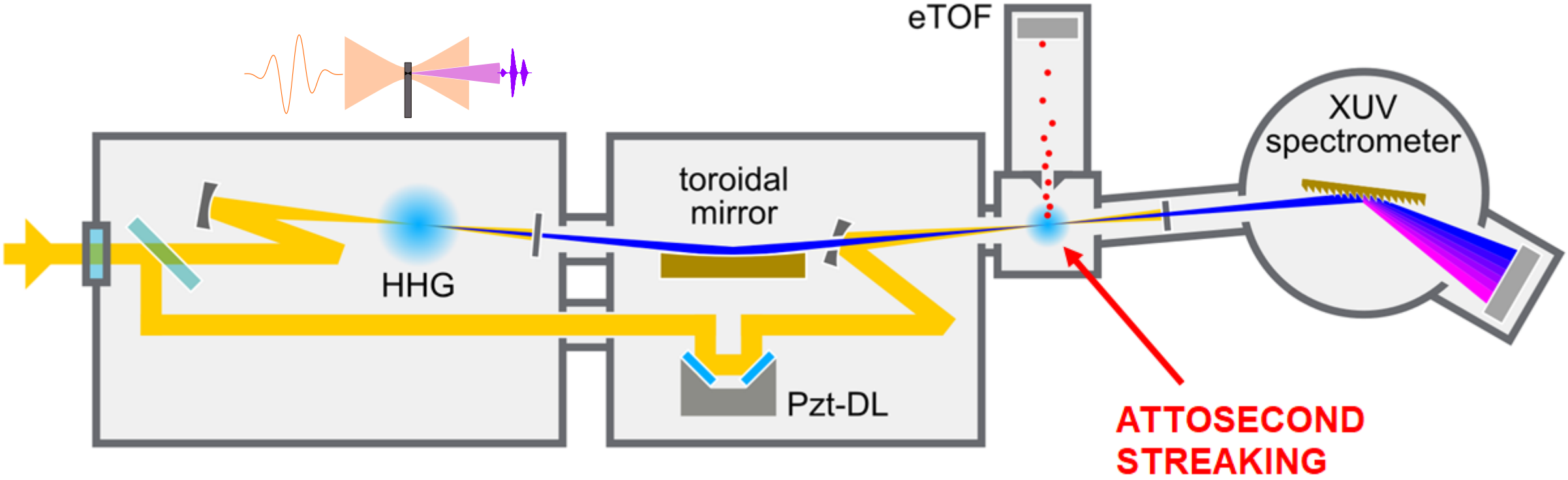
Coherent combination of CEP-stable ultrashort laser pulses



- CEP-stable seed
- Attosecond-synchronization
- Parallel scheme is scalable in:
  - Bandwidth
  - Pulse Energy
  - Output Power
  - (adaptable to novel pump lasers)

G. M. Rossi et al., Nature Photonics Vol.14, 629-635 (2020)

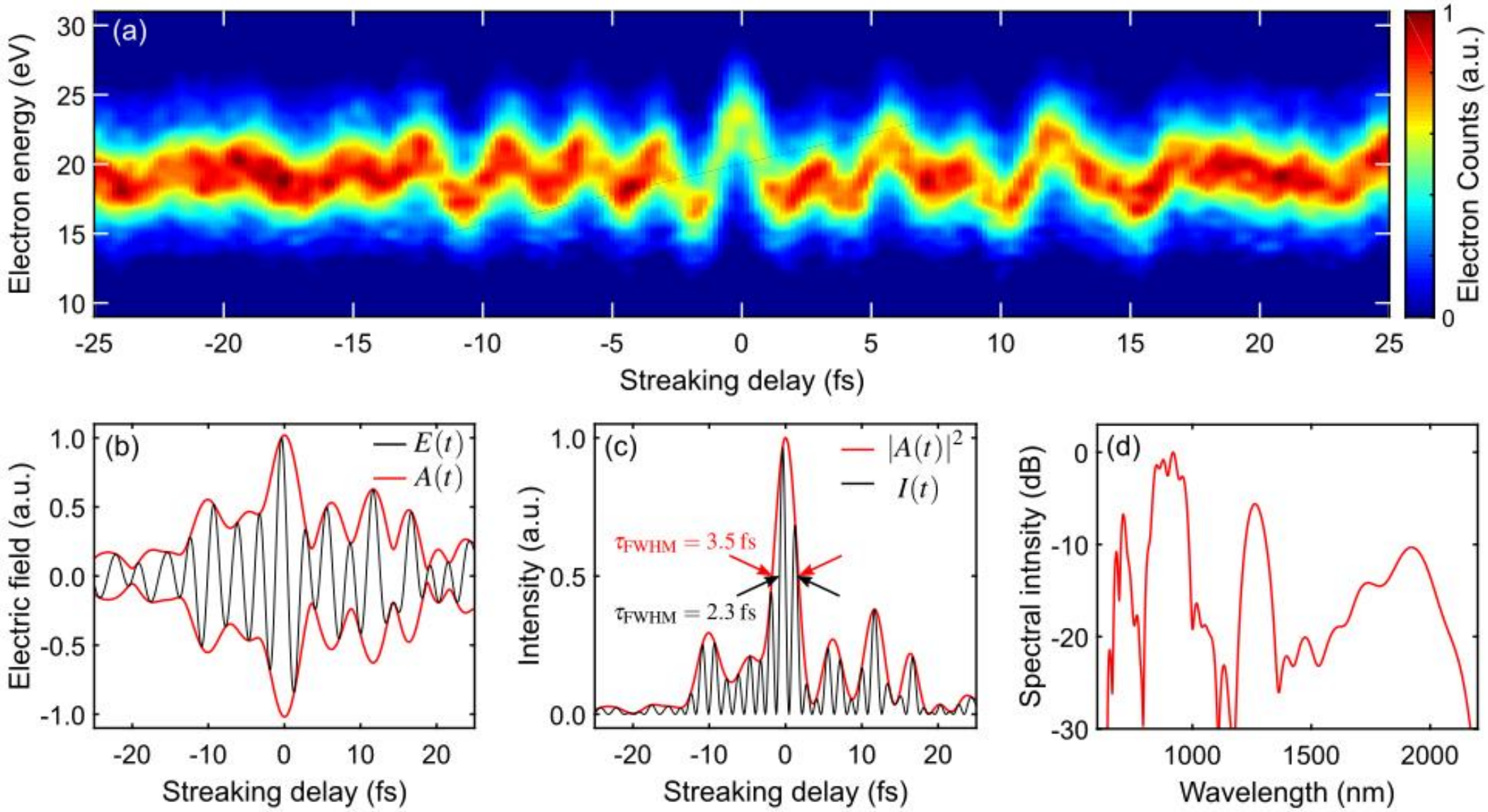
Pulse Measurement via Attosecond Streaking



Attosecond Streaking Setup:

- Attosecond pulse releases photo-electrons in streaking gas
- Photo-electron energy modulated by sub-cycle pulse
- Full time-domain reconstruction of synthesized pulses (incl. its CEP)

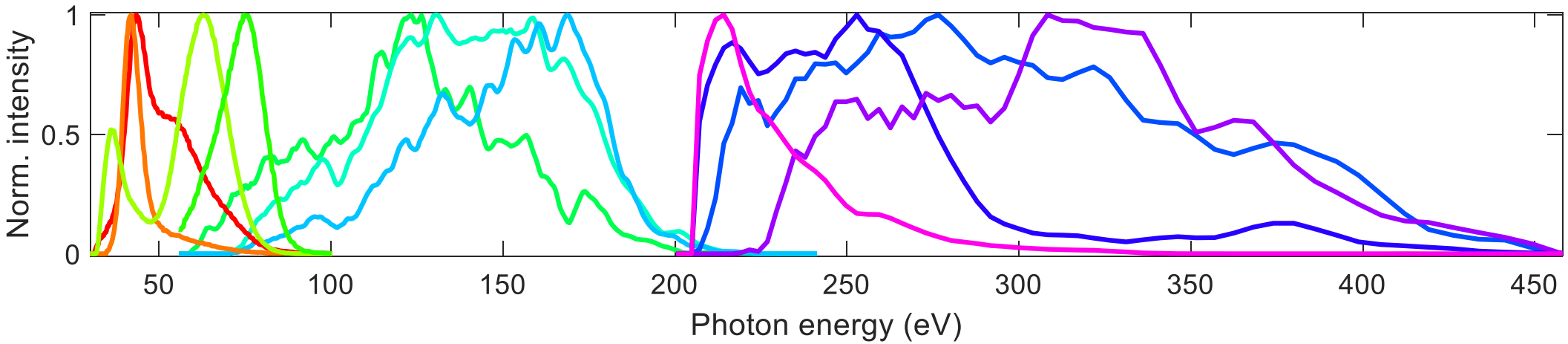
Attosecond Streaking of a Sub-Cycle Pulse



Tunable Isolated Attosecond Pulses

From XUV to soft X-Ray

Source Gas | **Argon 100s pJ** | **Neon 10s pJ** | **Helium ~pJ**



Si **S** **C** **N** **O** **528eV**

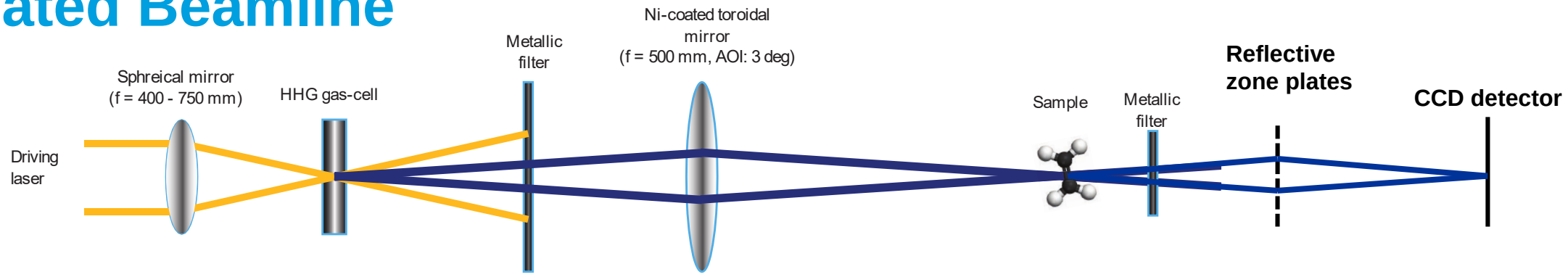
F. Calegari et al., Science 346 (6207), (2014)
- electron dynamics in phenylalanine

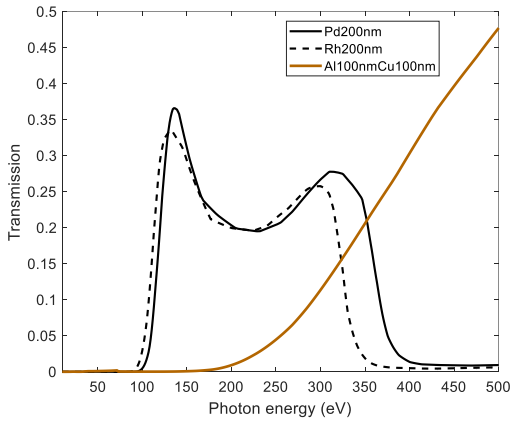
M .Schulze et al., Science 346 (6215), (2014)
- Band gap dynamics Si

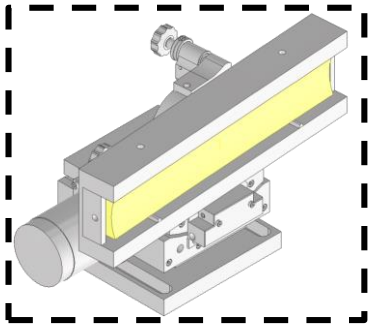
N.Saito et al., Optica 6 (1542-1546), (2019)
- ATAS on NO (N-edge)

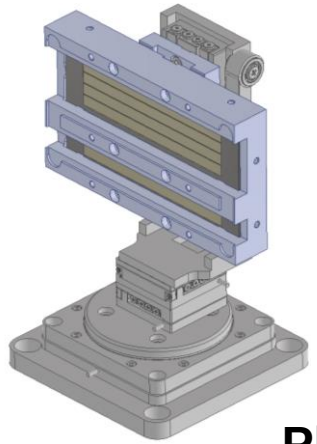
Y. Pertot et al., Science 355 (6322), (2017)
- SF_6 (sulfur edges, sub 200 eV)
- CF_4 (carbon edges, ~300 eV)

Updated Beamline







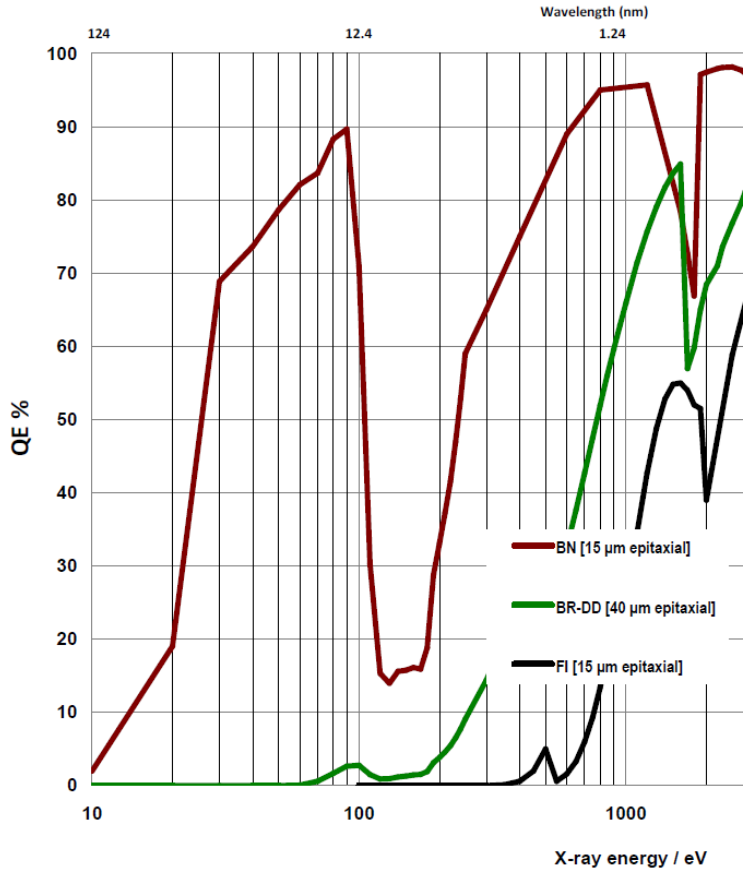


- Attosecond pulse generation in Argon/Neon/Helium
- Laser pulse blocking with metal filters, XUV focusing with toroidal mirror
- Reflective zone plate (RZP) as spectrometer

Photon Flux

- 10^{10} ph/s @50 eV
- 10^{6} ph/s @250 eV
- 10^{5} ph/s @300 eV
- 10^{4} ph/s @400 eV per 1% BW

Detector: Commercial Silicon Based CCD



Ideal Detector

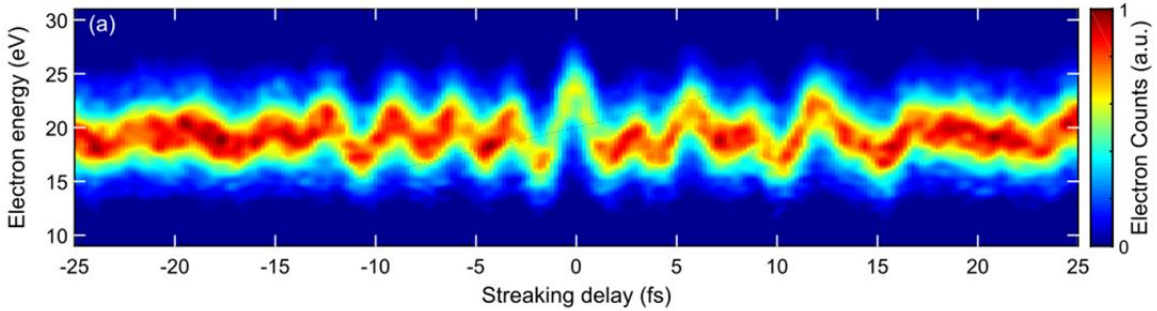
- 1-D with ~1k pixels
- IR/VIS blind (up to 3eV)
- Single photon counting
- msec to sec integration time
- Low/No Readout Noise

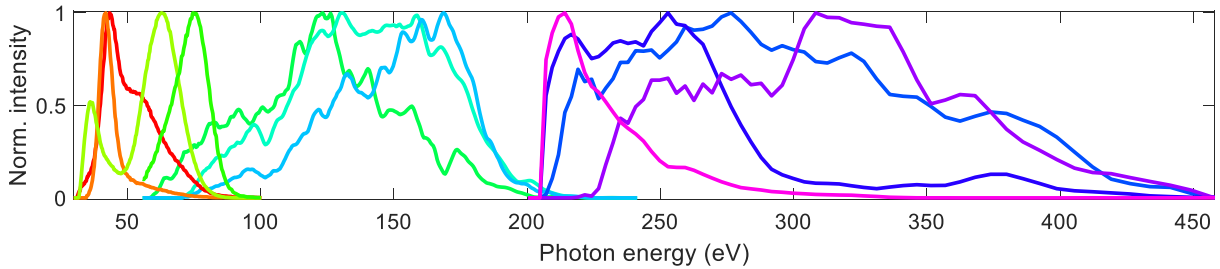
- Commercial silicon-based CCD (Andor Newton)
- back-illuminated and TEC-cooled to -40 °C
- Dark current: 0.2 e^-/sec, Readout Noise: 25 e^-/pixel, Well-Depth: 100 ke^-/pixel

Conclusion and Outlook

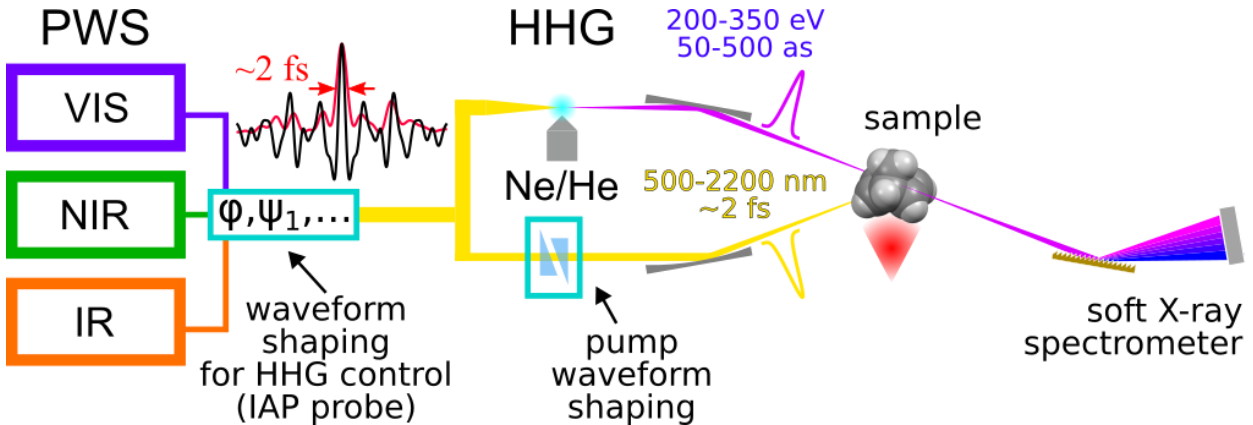
Demonstration of a novel laser technology and the implications for attosecond-resolved experiments

- Stable **sub-cycle pulse** generation
- Direct generation of **isolated attosecond pulses** via HHG
- Manifold **shaping** of the attosecond pulses
- Attosecond streaking for full reconstruction of the synthesized field
- HHG reaching the **water-window** (280-530eV)



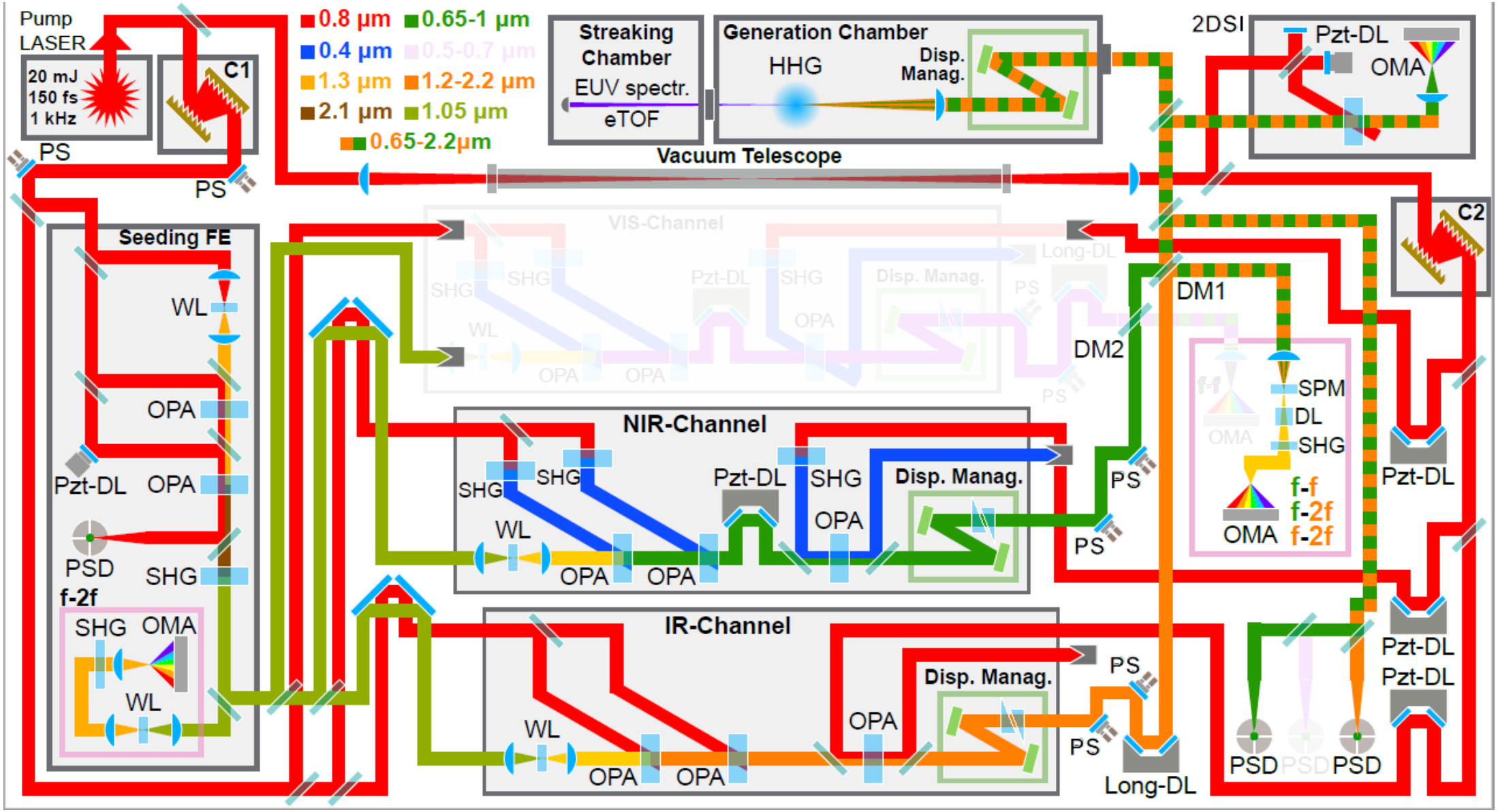


- *Sub-Cycle/Attosecond pump-probe experiments*



Thank you for your attention!

Our Current Implementation



Rossi et al., Nature Photonics 2020

Highly Tunable IAP generation

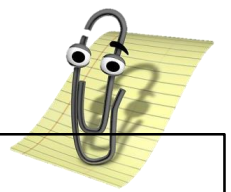
HHG-continua in argon and neon under similar experimental conditions

HHG/IAP tunability:

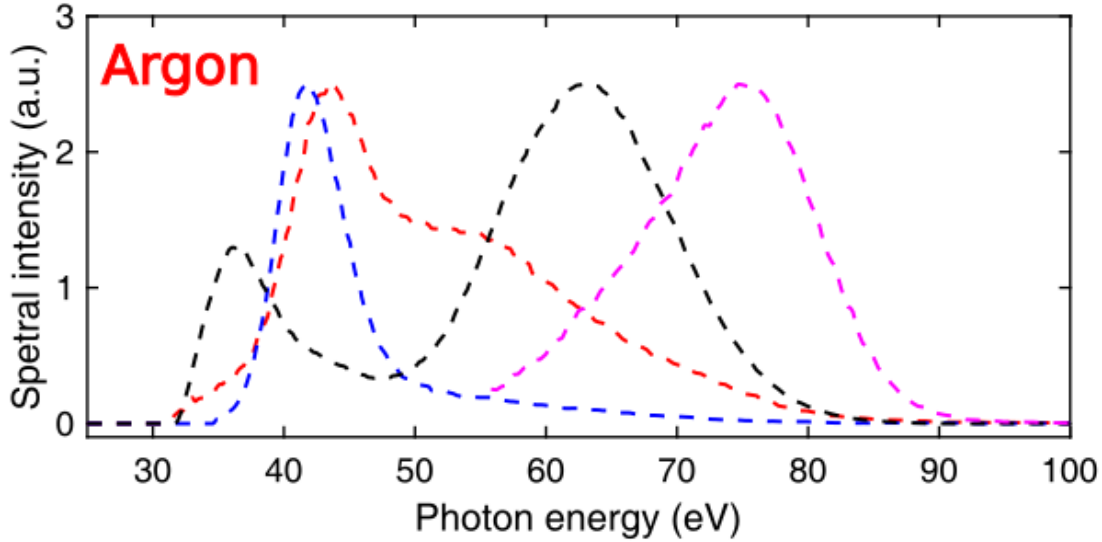
- Spectral shape
- Bandwidth
- Central energy
- HHG Yield

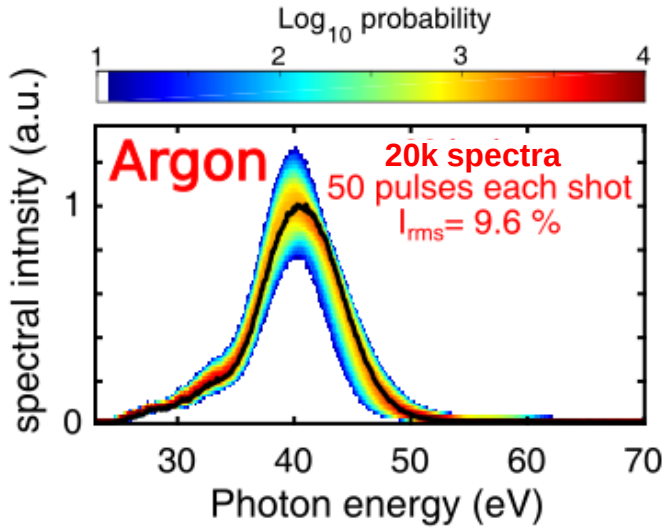
Simply by changing:

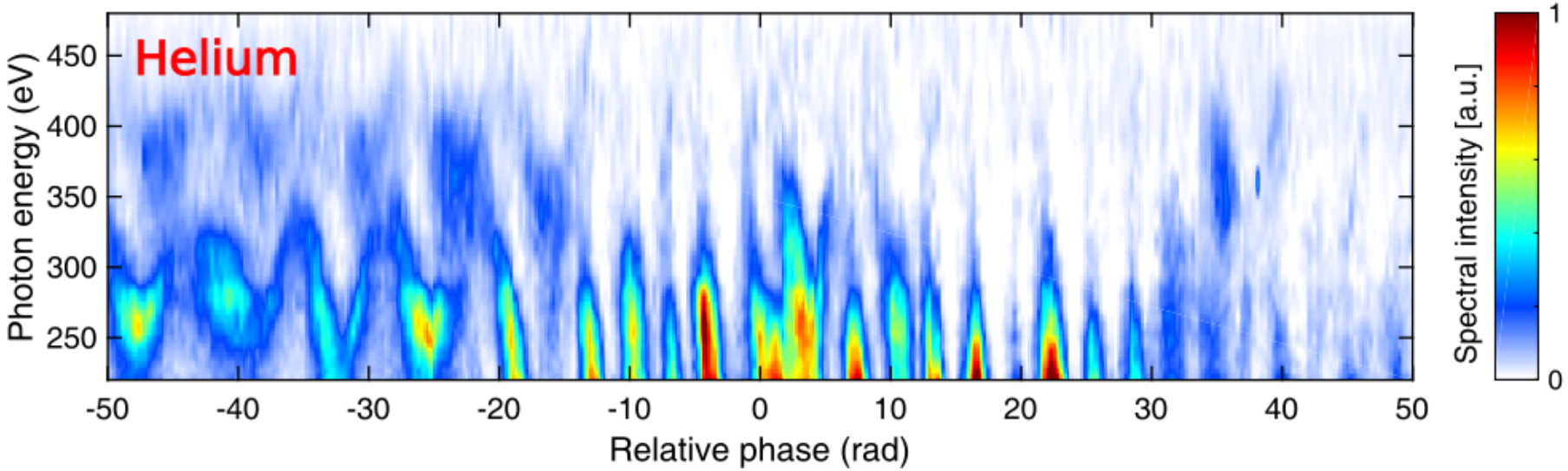
- HHG source gas
- Synthesis parameters



Check **Talk on Wednesday**:
„Soft X-ray continua generation via HHG with sub-cycle synthesized laser fields “

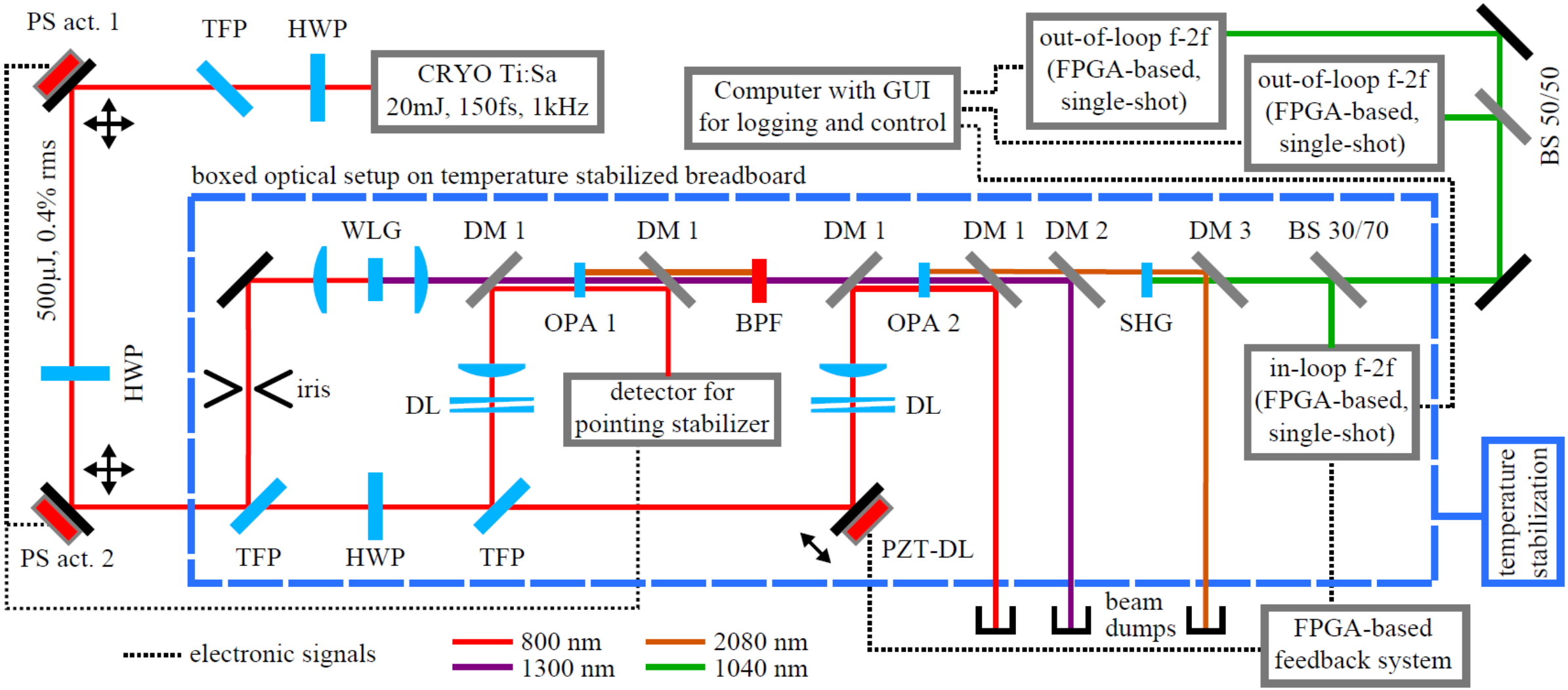






Y. Yang et al., Nat. Comm. 12, 6641 (2021).

CEP-stable seeding front-end



Stabilizing and Controlling the Synthesized Waveform

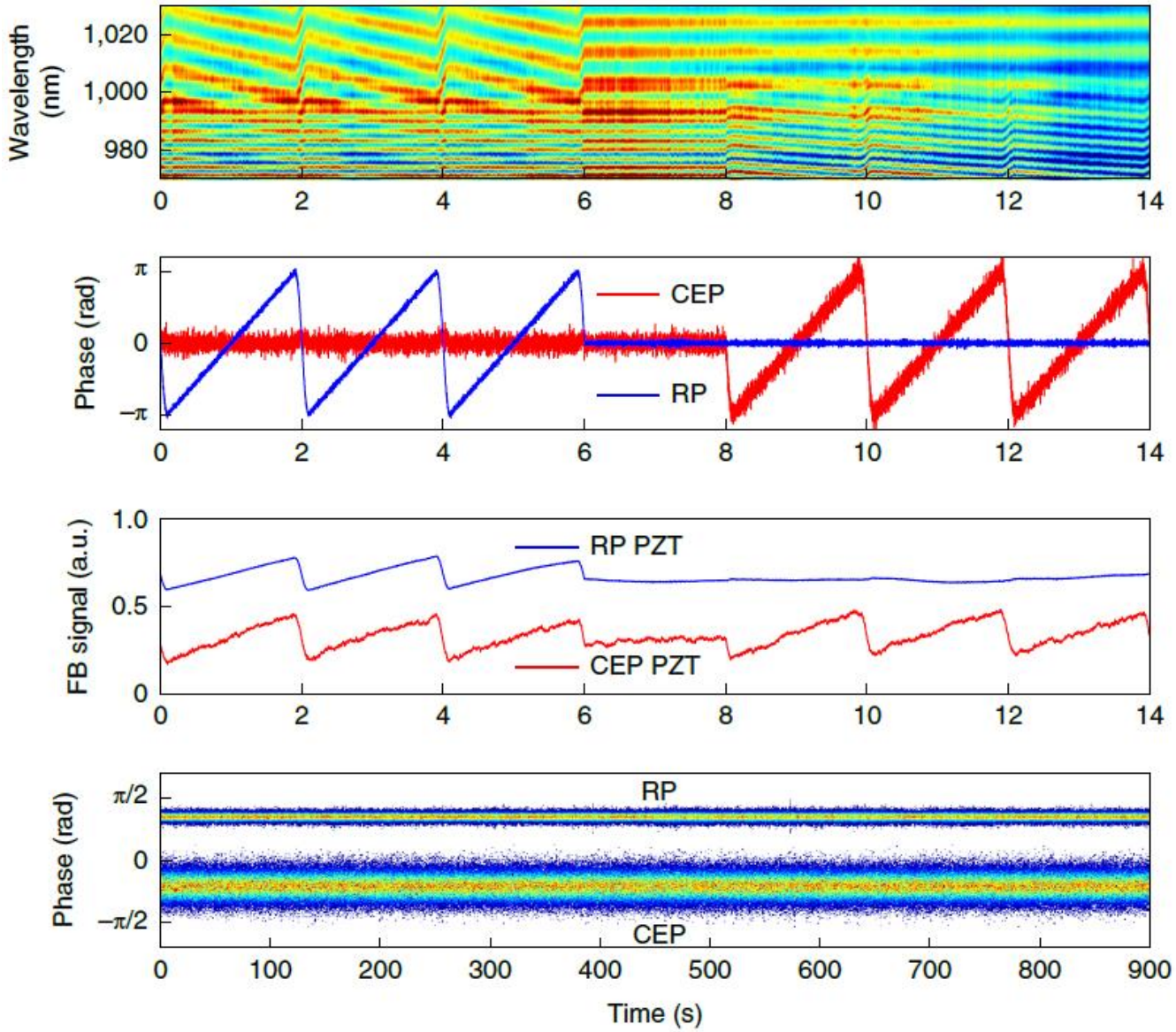
Phase-Coherent Synthesis

System Configuration:

- In-Line Dual Phase Meter with single-shot spectrometer
- FPGA-based feedback
- Several actuators:
  - Short/long range
  - affect CEPs/RP/Delays

Phase Stability:

- 180-250 mrad CEP rms
- 50-80 mrad RP rms
- **Hours of stable phase-locks**



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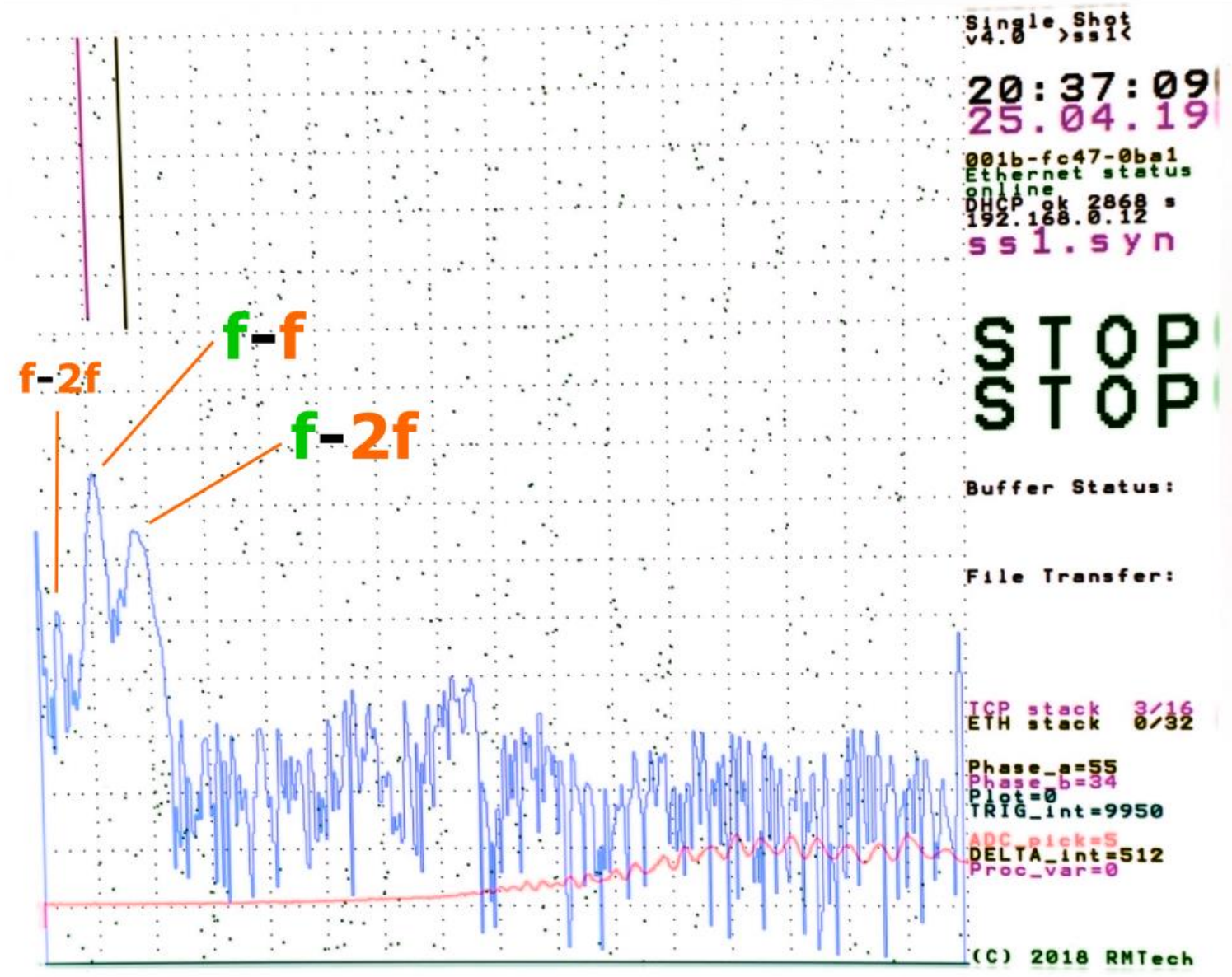


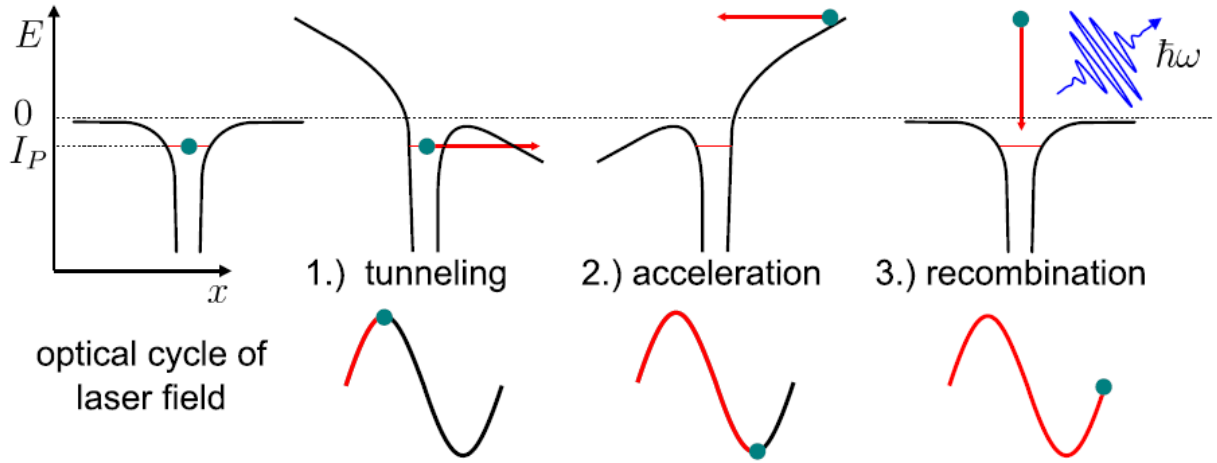
Entering the Realm of Attoseconds

High Harmonic Generation (HHG) at the forefront of ultrafast science

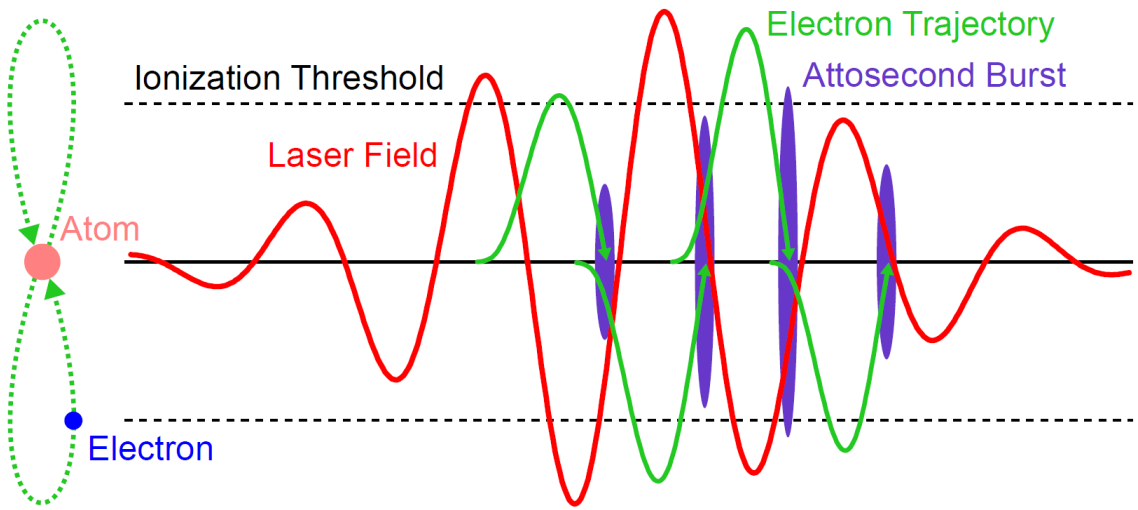
HHG provides:

- Pulses in the XUV to soft X-ray
- Attosecond pulses from femtosecond laser pulses
- up to keV photon energy
- BUT: low efficiency

3-Steps of HHG:



HHG driven by Few-Cycle Pulses:



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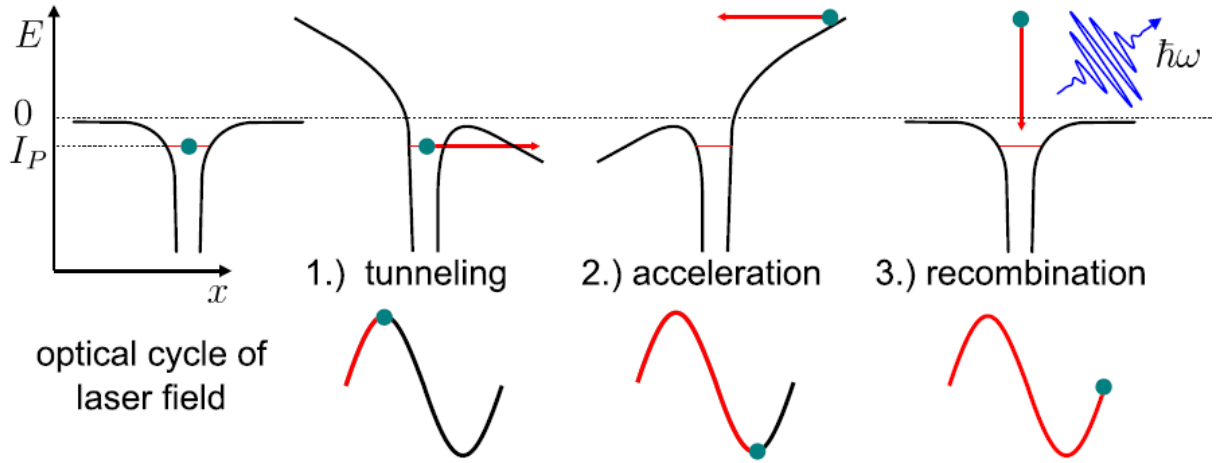
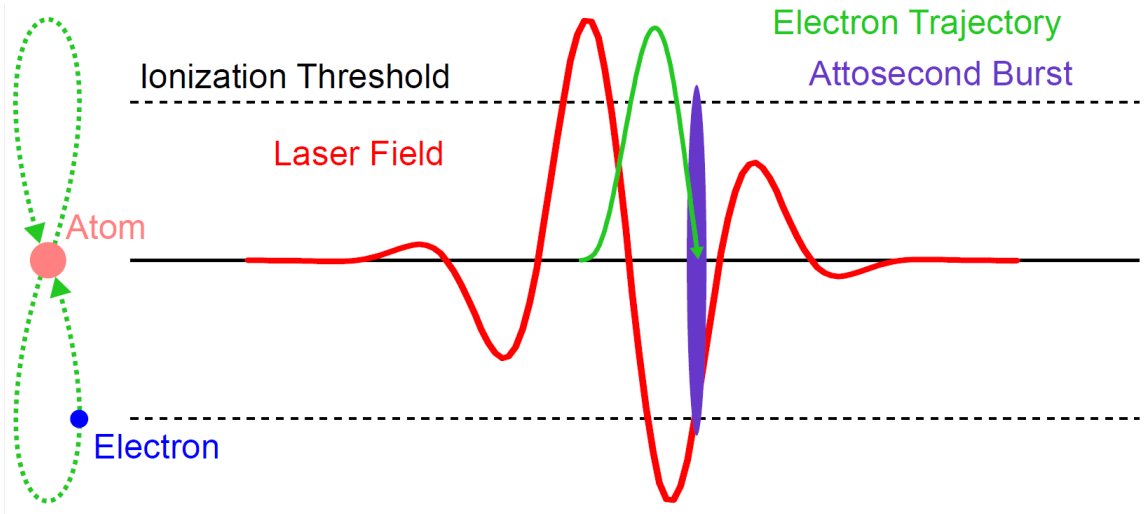


HHG driven by Sub-Cycle Pulses:



Sub-cycle pulses eliminates need for gating techniques

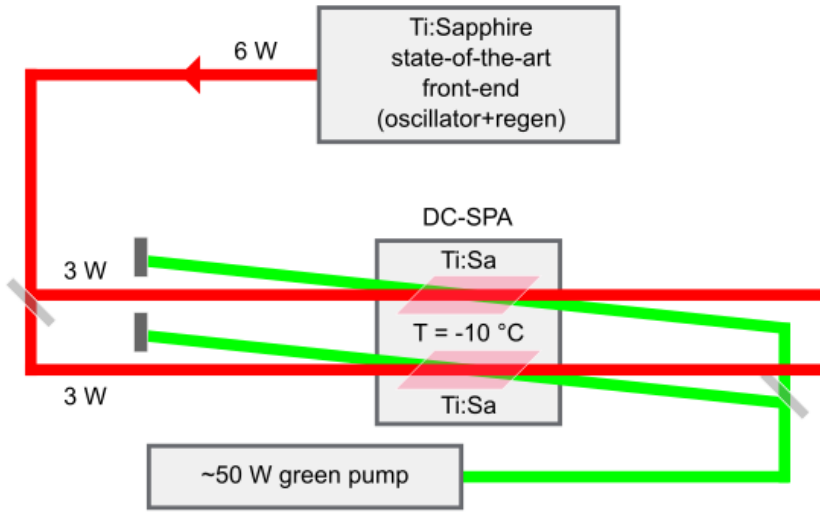
Non-sinusoidal waveforms control the HHG and can increase its efficiency

Roadmap to novel pump laser technologies

Multi-Beam Pump Laser Systems

- Multiple OPAs > Multiple Pump Beams
  - Further scaling of Ti:Sa technology & avoiding cryo-cooling
  - Synthesizer immune to inter-amplifier temporal jitter (few fs)
- Synthesizer adaptable to few-ps pump lasers (Ytterbium)

Current pump pulse duration:
150 fs, 1 kHz Rep.-Rate



R. E. Mainz, Optics Express Vol.31 (7) (2023)

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Multi-Beam Pump Laser Systems

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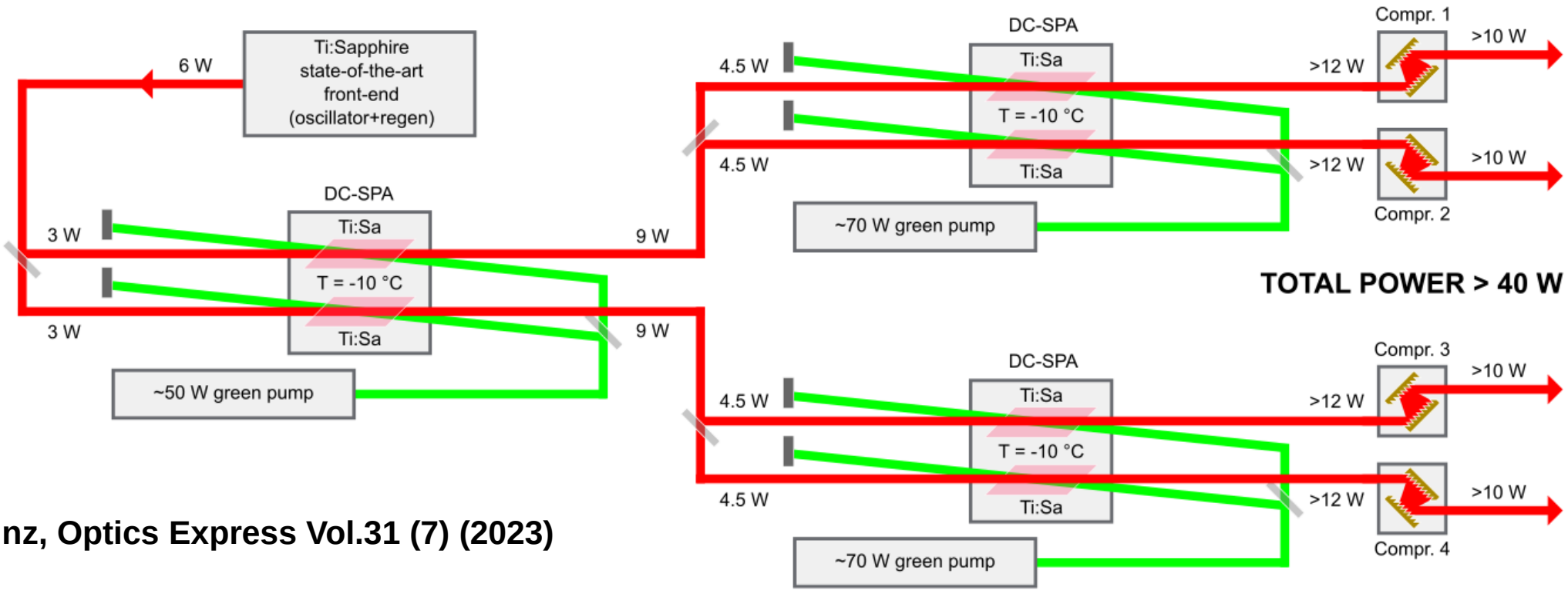
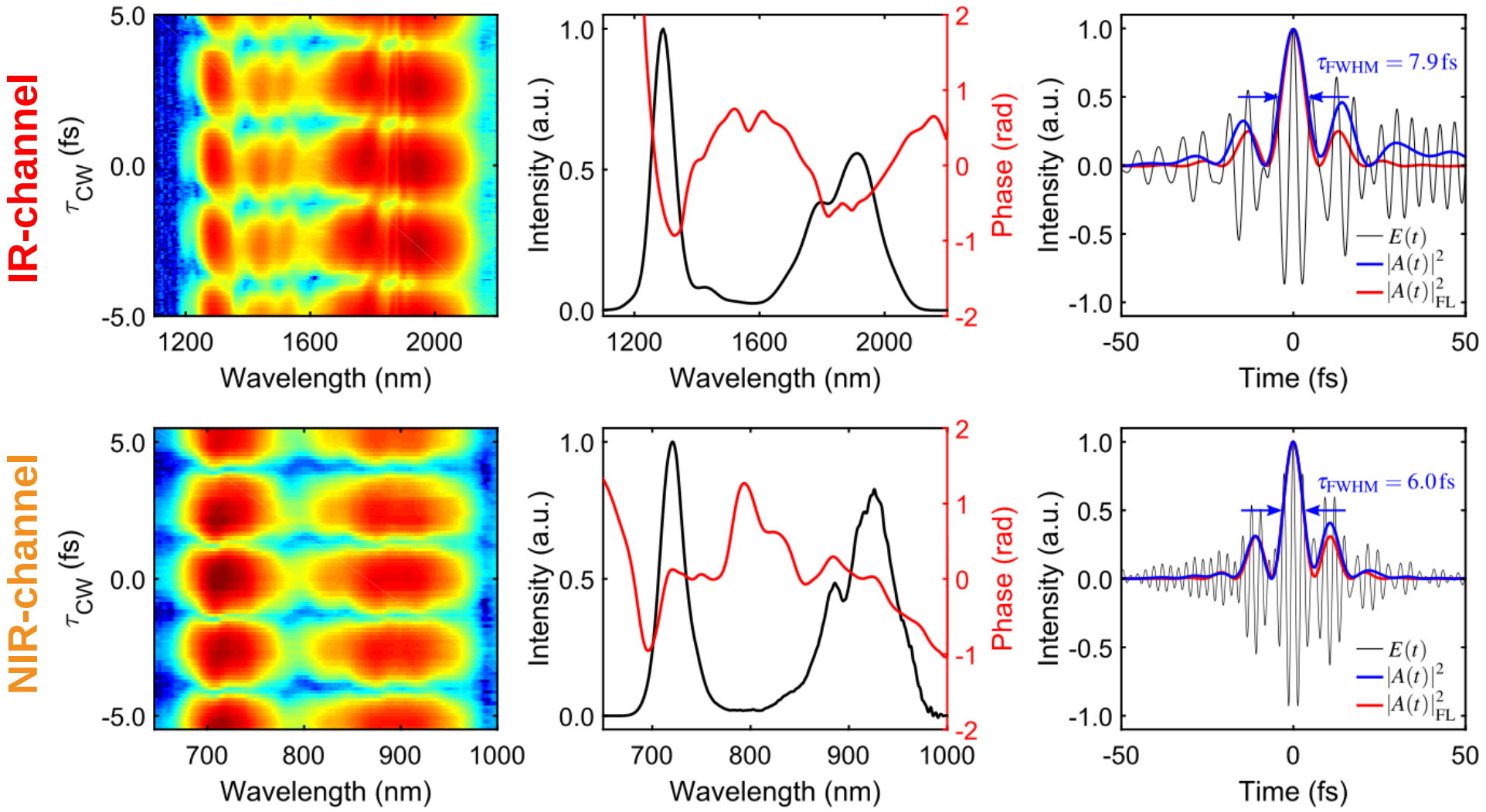


R. E. Mainz, Optics Express Vol.31 (7) (2023)

Few-Cycle Pulses from each Spectral Channel

Pulses characterized via 2-dimensional spectral shearing interferometry (2DSI)

- **IR-channel:**
  - 1200-2200 nm
  - 7.9 fs
  - 500 µJ
- **NIR-channel:**
  - 650-1000 nm
  - 6.0 fs
  - 100 µJ
- **(VIS-channel:)**
  - 500-700 nm
  - ~ 6 fs
  - 150 µJ



Stabilizing and Controlling the Synthesized Waveform

.... with attosecond precision

Synchronization System:

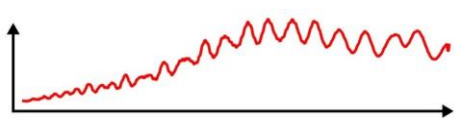
- In-Line Dual Phase Meter with single-shot spectrometer (right)
- FPGA-based feedback system
- Several timing actuators:
  - short- and long-range stages
  - affect CEPs/RP/Delays

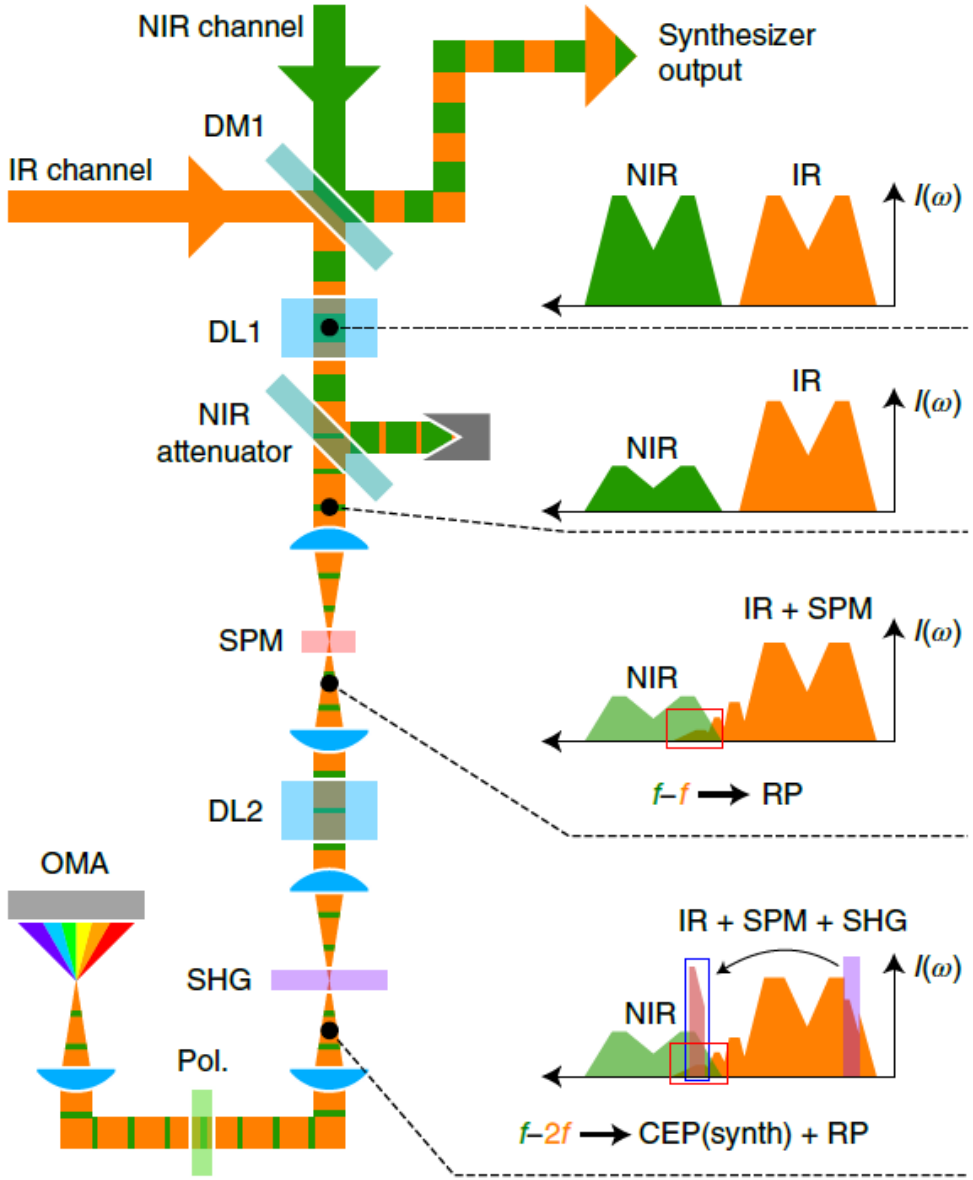
CEP-noise: 250 mrad rms

RP-noise: 80 mrad rms

- (1-4 % of waveform period)

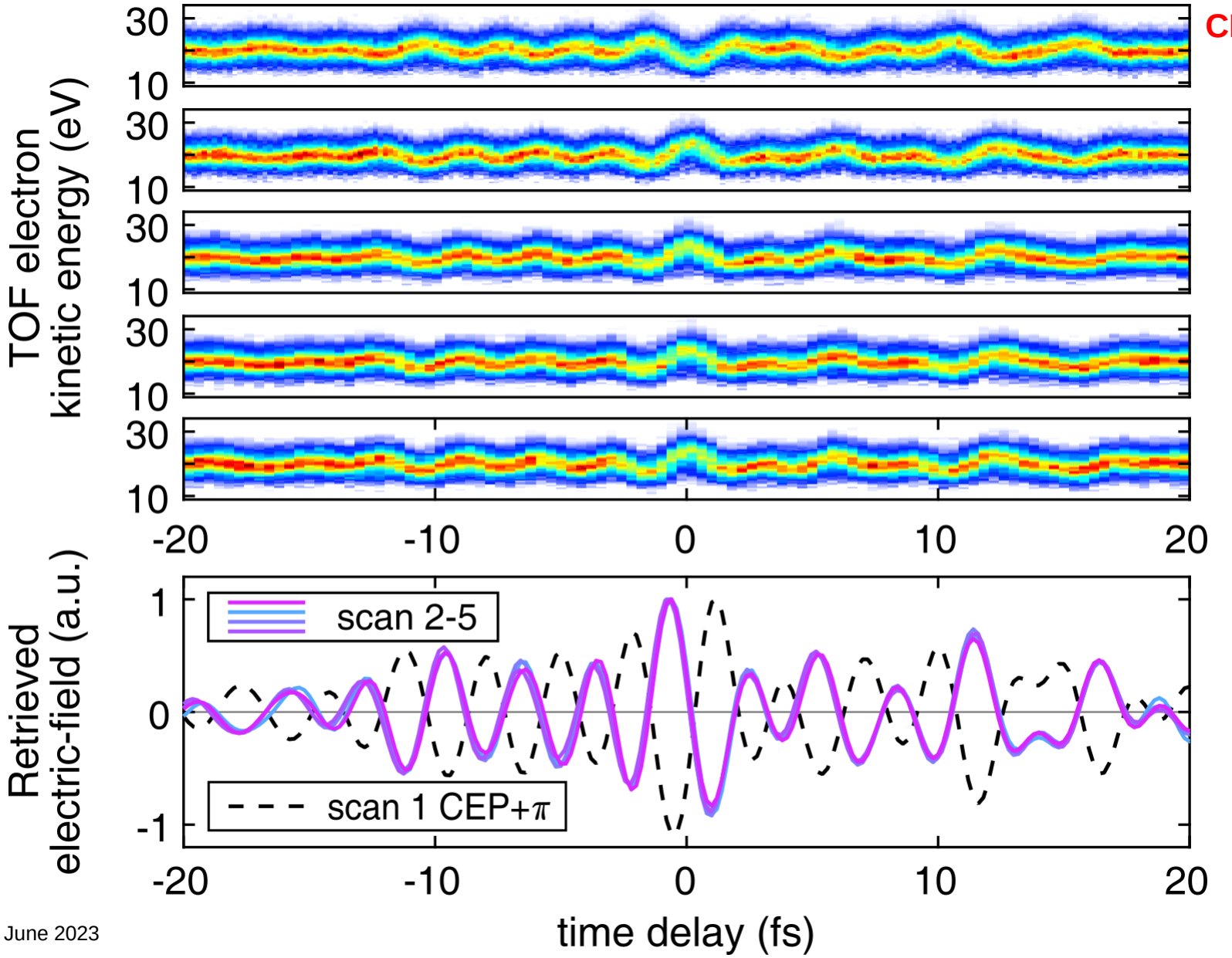
observed spectral interference signal





Attosecond Streaking of a Sub-Cycle Pulse

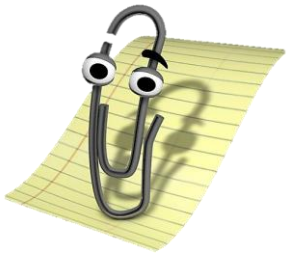
- Stable and repeatable waveforms over hours



HHG-emission in the Water-Window

HHG in high-pressure Helium

- Up to 10 bar pressure
- Increased intensity and bandwidth
- Cut-off up to 450 eV



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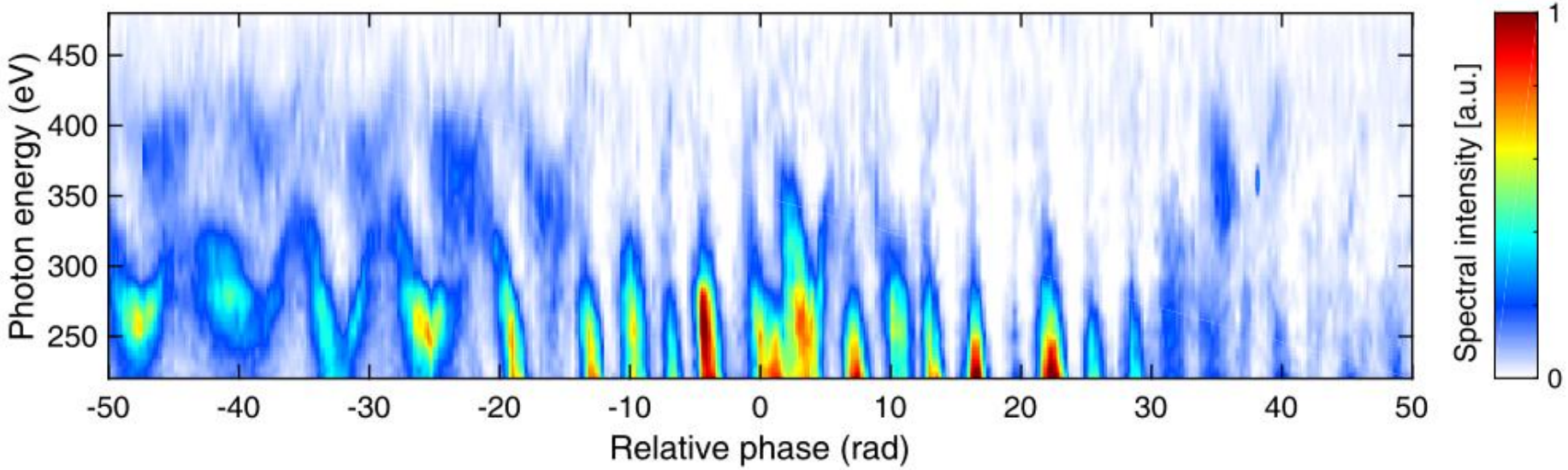
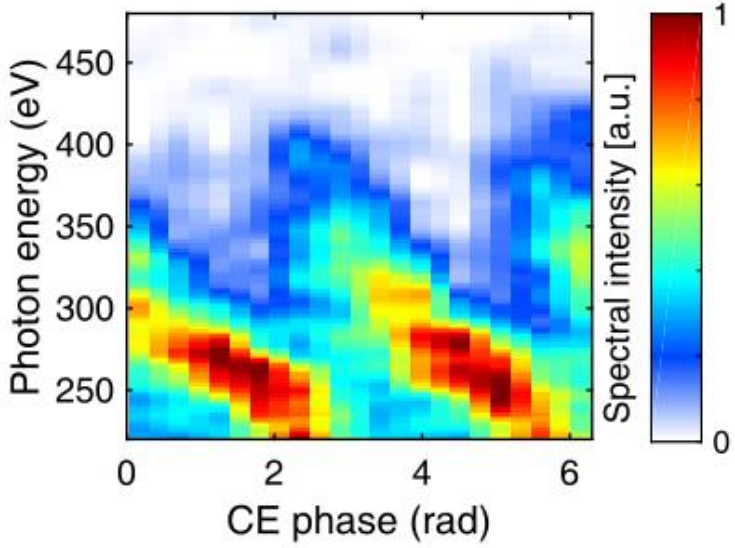
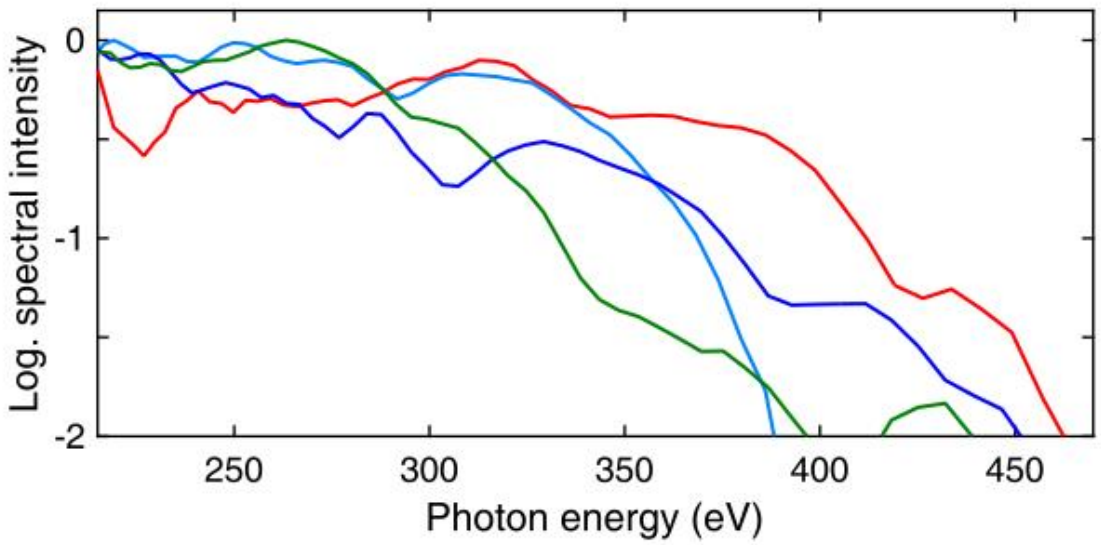
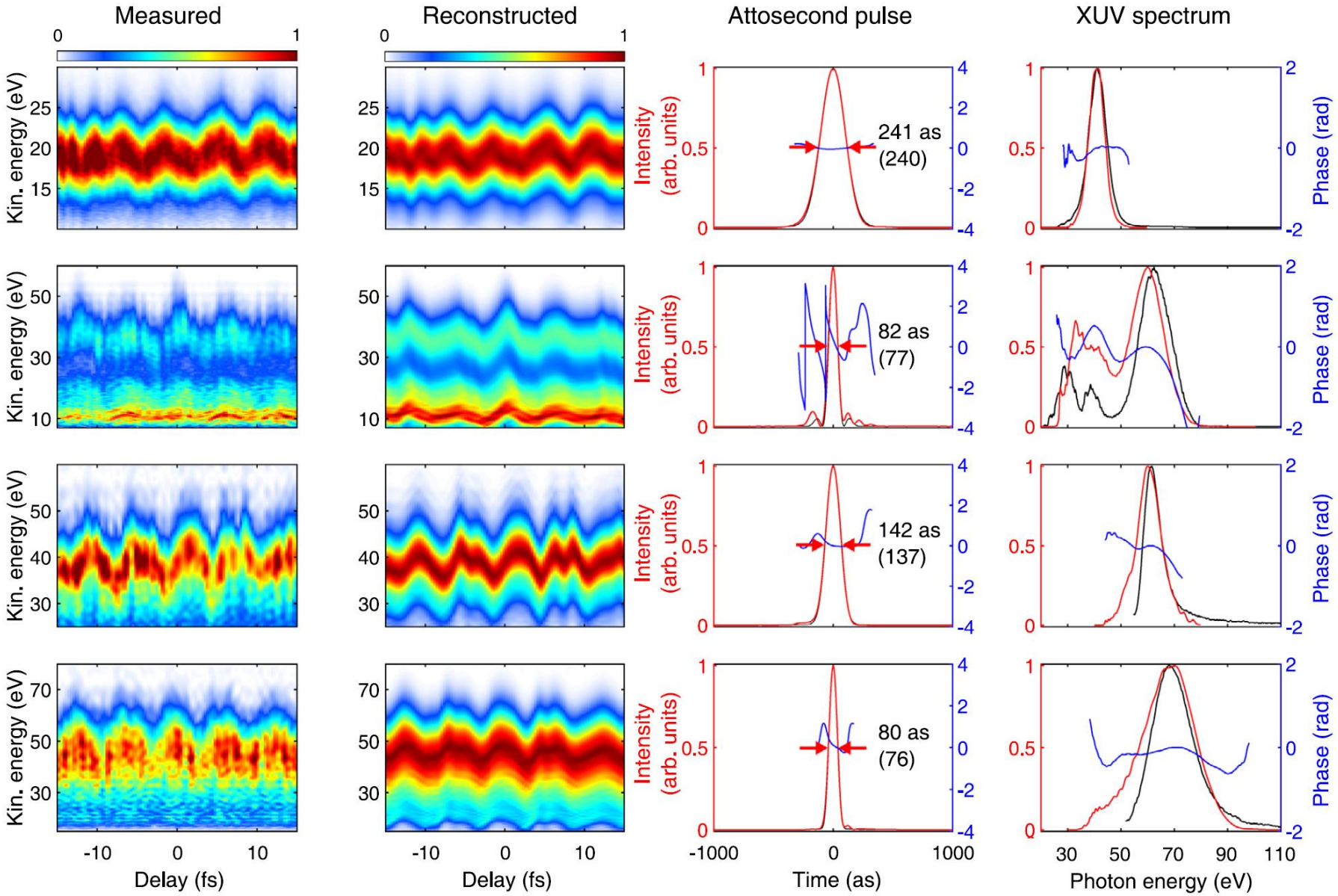






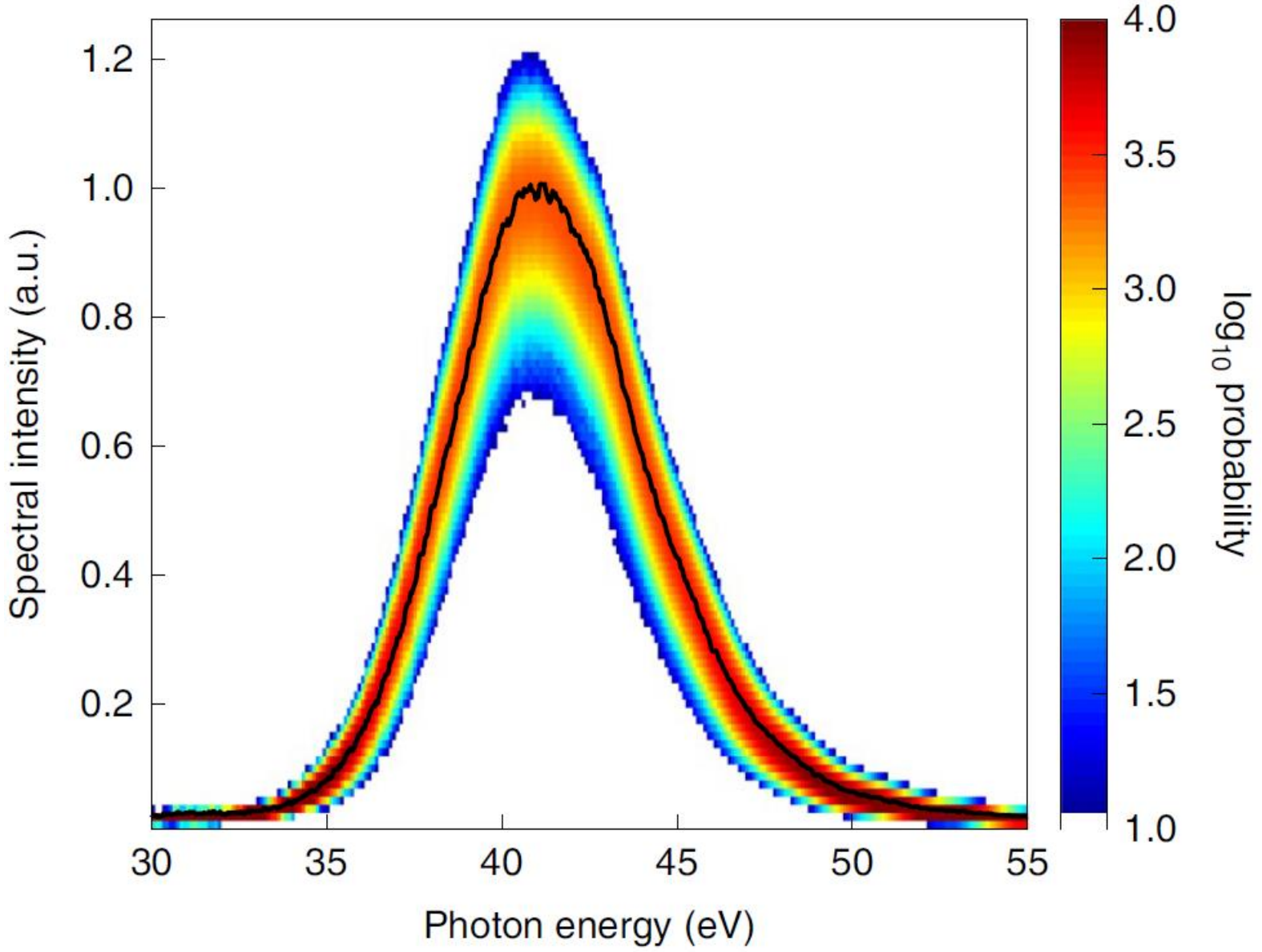
Highly Tunable IAP generation in Argon - 80 to 240 as



Y. Yang et al., Nat. Comm. 12, 6641 (2021).

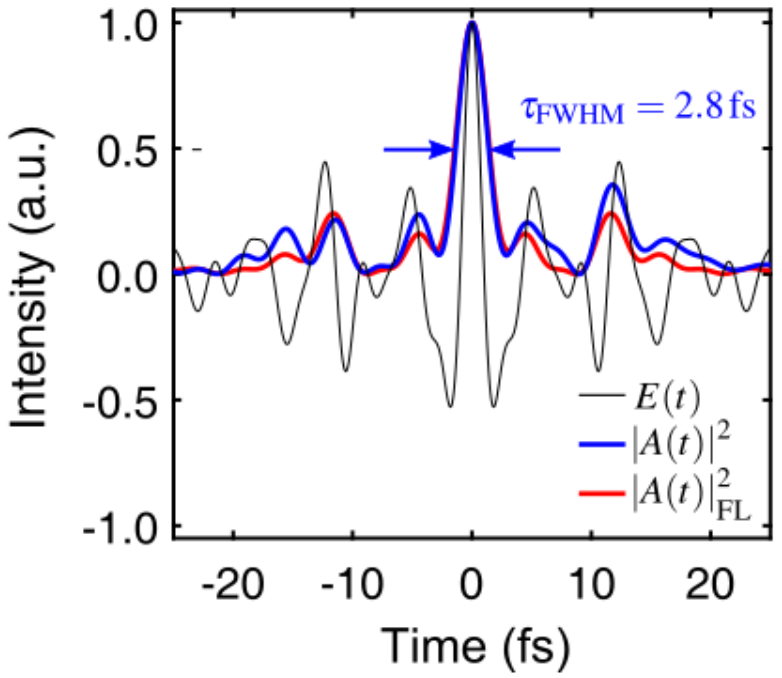
Stability of the Isolated Attosecond Pulse

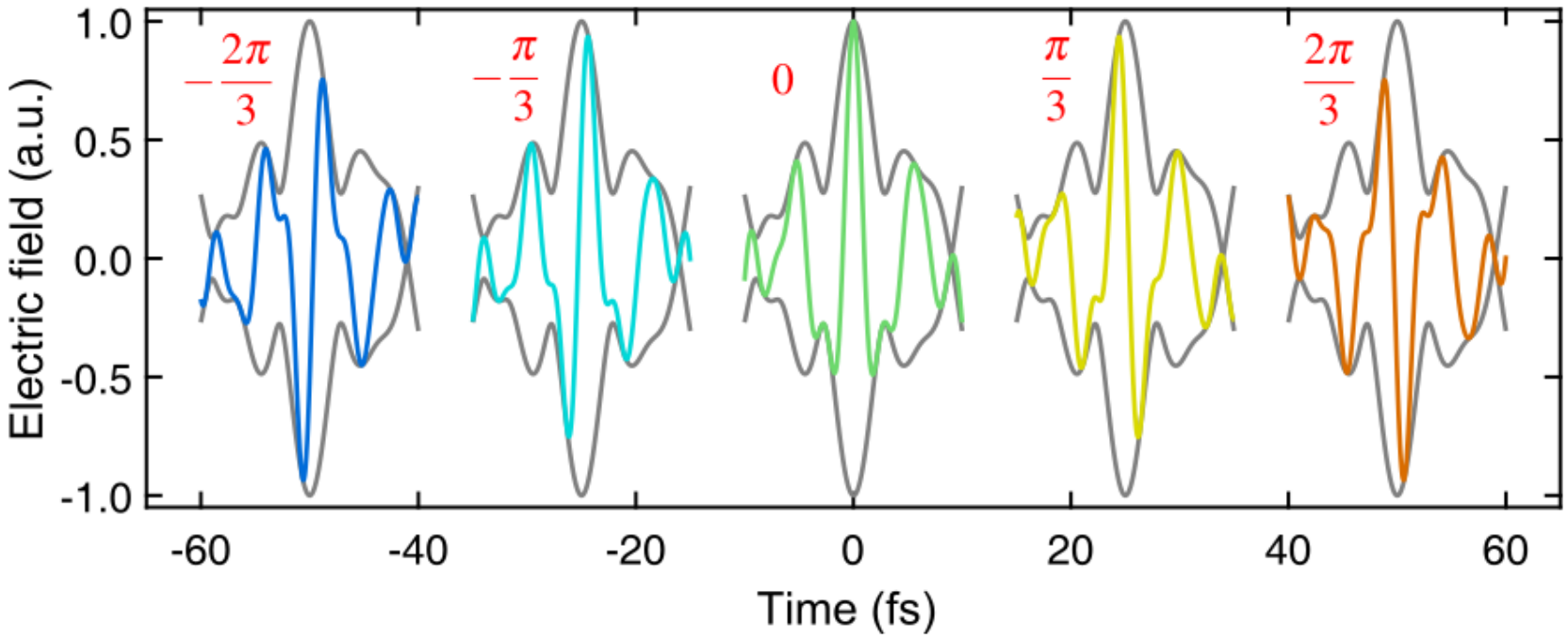
- Remarkably stable HH-spectrum
- Same spectral shape and IAP over hours
- 5.9 % rms (50 shots, 30 mins)



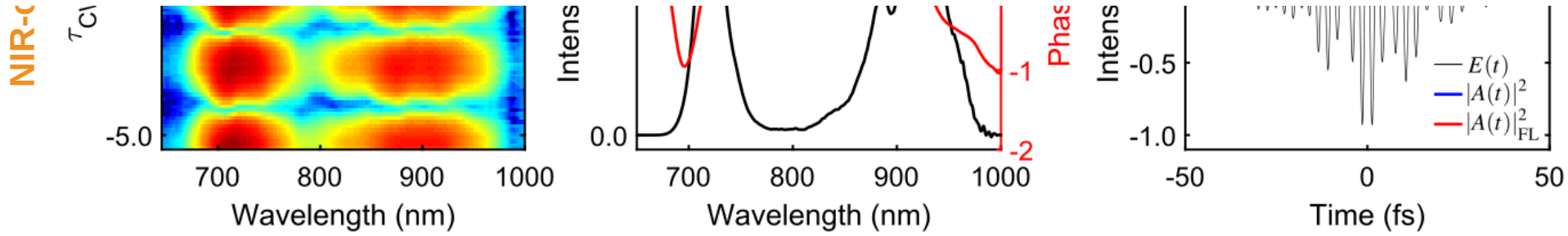
Few-Cycle Pulses from each Spectral Channel

Pulses characterized via 2-dimensional spectral shearing interferometry





- 500-700 nm
- ~6 fs
- 150 µJ

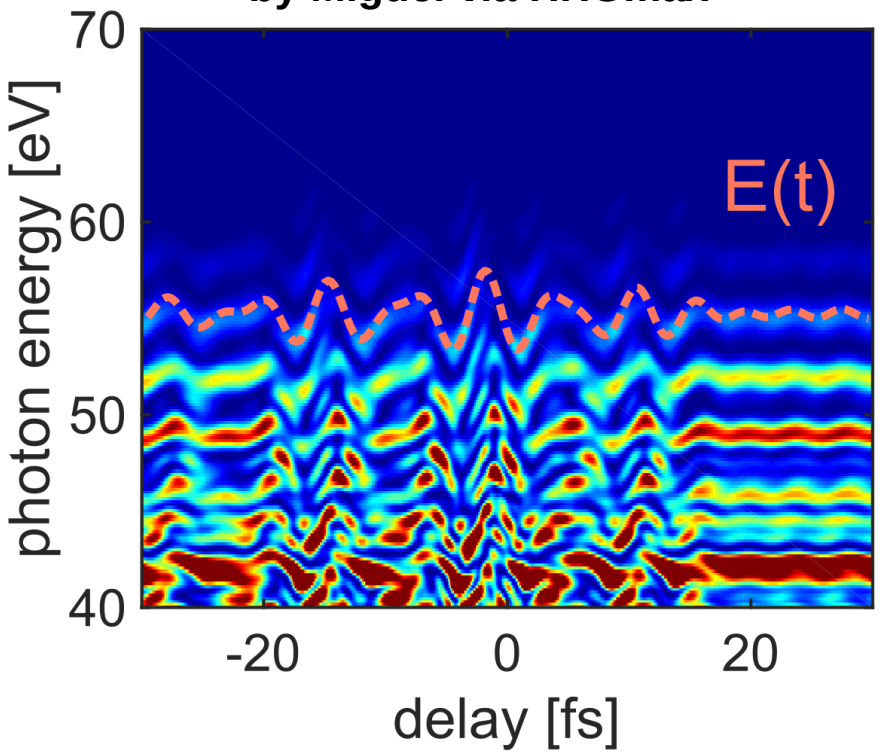


In-Situ Streaking aka ARIES

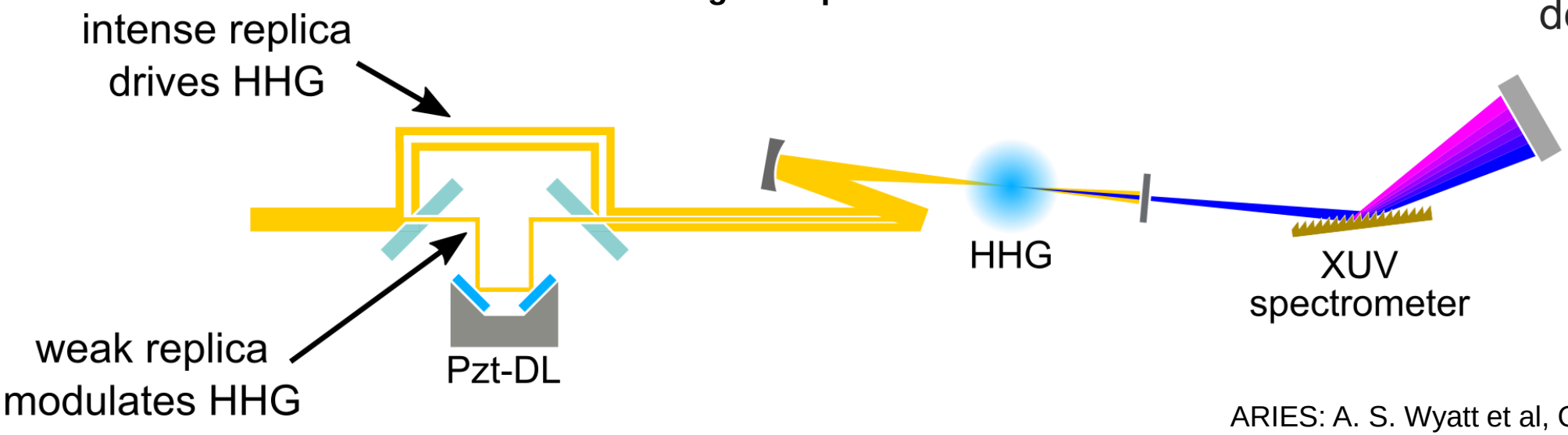
- Full Waveform reconstruction directly in the HHG gas jet
- No conversion to photo-electrons, all optical method

  > higher signal
- No TOF and their narrower detection bandwidth
- Direct XUV detection

In-Situ Streaking: Simulation by Miguel via HHGmax



In-Situ Streaking: Setup



ARIES: A. S. Wyatt et al, Optica 3, 303-310 (2016)