UNIVERSITÀ DEGLI STUDI DI TRIESTE

# Attosecond pulse shaping using an echo-enabled seeding mechanism

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SUMMARY

*The project aims to explore how intense, coherent extreme-ultraviolet light generated by seeded free-electron lasers can be used to investigate and control ultrafast electronic dynamics in matter. By studying the newly installed Echo-Enabled Harmonic Generation (EEHG) scheme on FERMI FEL-1, the project will develop methods to generate multiple phase-locked frequencies and tailored attosecond pulse trains. The goal is to uncover new regimes of light–matter interaction where strong-field physics, quantum optics, and attosecond science converge. This work will support the next-generation upgrades of FERMI and contribute to the broader QU-ATTO mission of merging quantum technologies with attosecond physics.*

Understanding and controlling the interaction between electromagnetic radiation and matter is central to modern physics and technology. From quantum materials to chemical dynamics, ultrafast processes occurring on the femtosecond and attosecond timescales govern how electrons move, bond, and interact. The development of high-brightness, ultrashort photon sources—such as high-harmonic generation (HHG) and free-electron lasers (FELs)—has revolutionized our capability to probe these processes with unprecedented temporal resolution.

Recent Nobel Prizes (2022, 2023) highlight the transformative importance of attosecond pulse generation and quantum optics. Their natural intersection is attosecond strong-field quantum optics, a rapidly emerging field aiming to combine the ultrashort temporal resolution of attosecond science with the concepts of coherence, entanglement, and quantum state manipulation traditionally studied in low-photon-number quantum optics.

Seeded FELs are uniquely positioned to advance this frontier. FERMI, the world's first fully seeded FEL in the XUV range, delivers pulses with exceptional temporal coherence, intensity, and tunability. The recent installation of the Echo-Enabled Harmonic Generation (EEHG) scheme on FERMI FEL-1 marks an important milestone toward its full upgrade to FERMI 2.0. EEHG provides unprecedented flexibility in tailoring the temporal and spectral structure of FEL radiation. Using two seed lasers and two dispersive sections it allows the generation of high harmonics with fine control over phase, frequency composition, and coherence properties.

This PhD project (DC10 of QU-ATTO) will exploit the EEHG configuration as a platform for advancing attosecond strong-field quantum optics. The unique ability of EEHG to disentangle seed-induced energy modulations from pre-existing electron-beam imperfections creates an ideal testbed for precise waveform synthesis and multicolor FEL generation. The research will explore how multiple frequency components can be simultaneously generated, phase-locked, and used to drive controlled ultrafast dynamics in matter.

The project includes four main research directions:

Machine studies of the newly installed EEHG system on FERMI FEL-1
This involves direct participation in the commissioning, optimization, and diagnostic development of the EEHG source. Activities will include working with seed laser systems, fine-tuning modulator parameters, measuring bunching factors and phase-space evolution, and contributing to machine shifts and operations.

Investigation of multicolor generation in HGHG and EEHG
Both High-Gain Harmonic Generation (HGHG) and EEHG routes offer complementary strategies for synthesizing multiple frequencies. The PhD will explore the parameter regimes allowing simultaneous harmonic generation, spectral shaping, and phase control, to enable new spectroscopy and control applications.

Machine-physics experiments on phase-locked multicolor generation
Phase locking between harmonic components is critical for generating attosecond pulse trains and engineered waveforms. This part of the project will involve experimental studies of harmonic coherence, temporal jitter, seeding-phase stability, and electron-beam–laser synchronization.

Implementation of frequency-synthesis experiments for attosecond waveform control
Using both HGHG and EEHG, the project will participate in advanced FEL experiments targeting waveform-controlled attosecond pulse trains. These include chirped-pulse amplification studies, multicolor attosecond bursts, and other techniques central to the QU-ATTO mission.

Overall, this project aligns directly with QU-ATTO's objectives:

Merging quantum-optics concepts with attosecond physics, and

Demonstrating coherent control in systems of increasing complexity using cutting-edge photon sources.

The combination of machine physics, advanced FEL theory, numerical modelling, and hands-on experimental work will provide a multidisciplinary and intersectoral training environment. The expected outcomes will support both the long-term upgrade strategy of FERMI and the broader European effort to develop next-generation attosecond and quantum-optical technologies.

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Supervisor 1: *Luca Giannessi*
Supervisor 2: *Claudio Masciovecchio*
Supervisor 3: Markus Gühr

List of courses to be taken (pending confirmation)

| Title | Teacher | CFU | Hours |
|---|---|---|---|
| Principles of Free-Electron Laser Physics | LUCA GIANNESSI | 2 | 16 |
| Free electron laser and synchrotron-based spectroscopies: getting to the nanometer with femtosecond resolution | CLAUDIO MASCIOVECCHIO | 2.5 | 20 |
| Modern tools for computational physics | DANIELE COSLOVICH | 1.5 | 12 |
| Advanced data analysis techniques with machine and deep learning | GRAZIA LUPARELLO | 2 | 16 |
| | | | |
| | | *8* | *64* |

List of interdisciplinary courses to be taken (pending confirmation)

| Title | Teacher | CFU | Hours |
|---|---|---|---|
| Academic English | DR001 | 4 | 32 |
| English for STEM | DR002 | 2 | 16 |
| THE PHD IN PERSPECTIVE: GUIDANCE FOR A MINDFUL CAREER DEVELOPMENT | DR019 | 2 | 16 |
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| | | *8* | *64* |