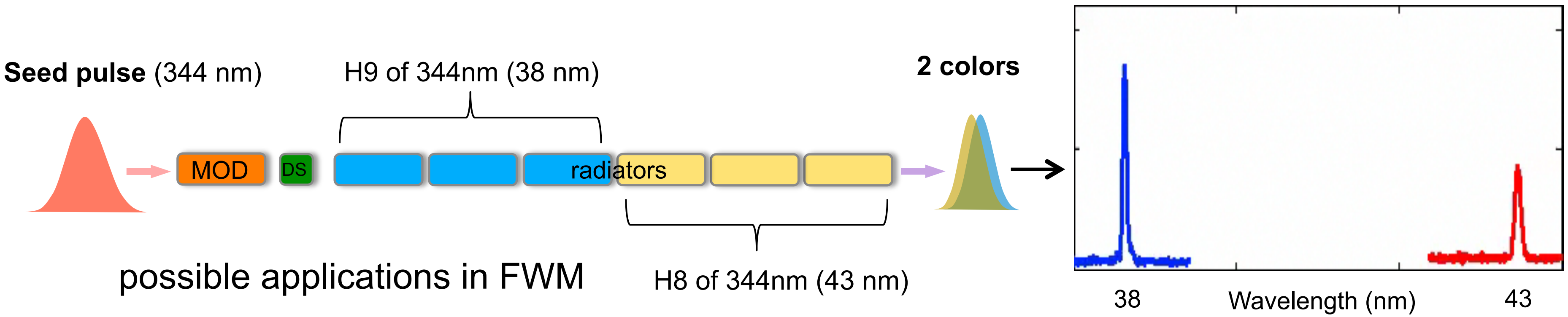
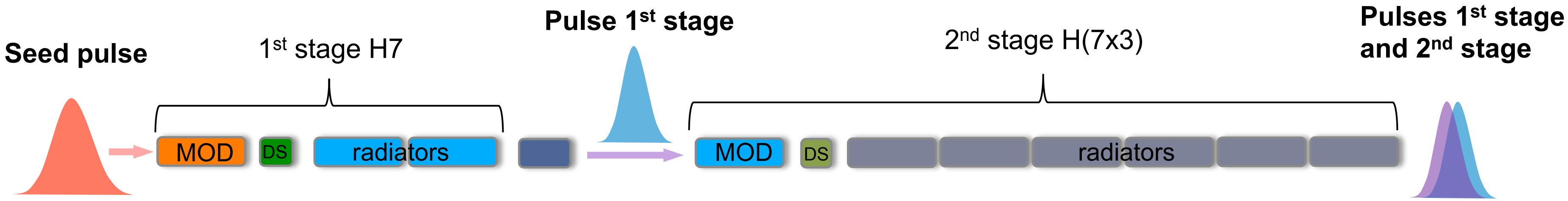
TWO COLOR OPERATION AT THE FERMI SEEDED FEL: ONE SEED PULSE

One seed pulse –> two color "zero-delay" FEL pulses using the split undulator scheme



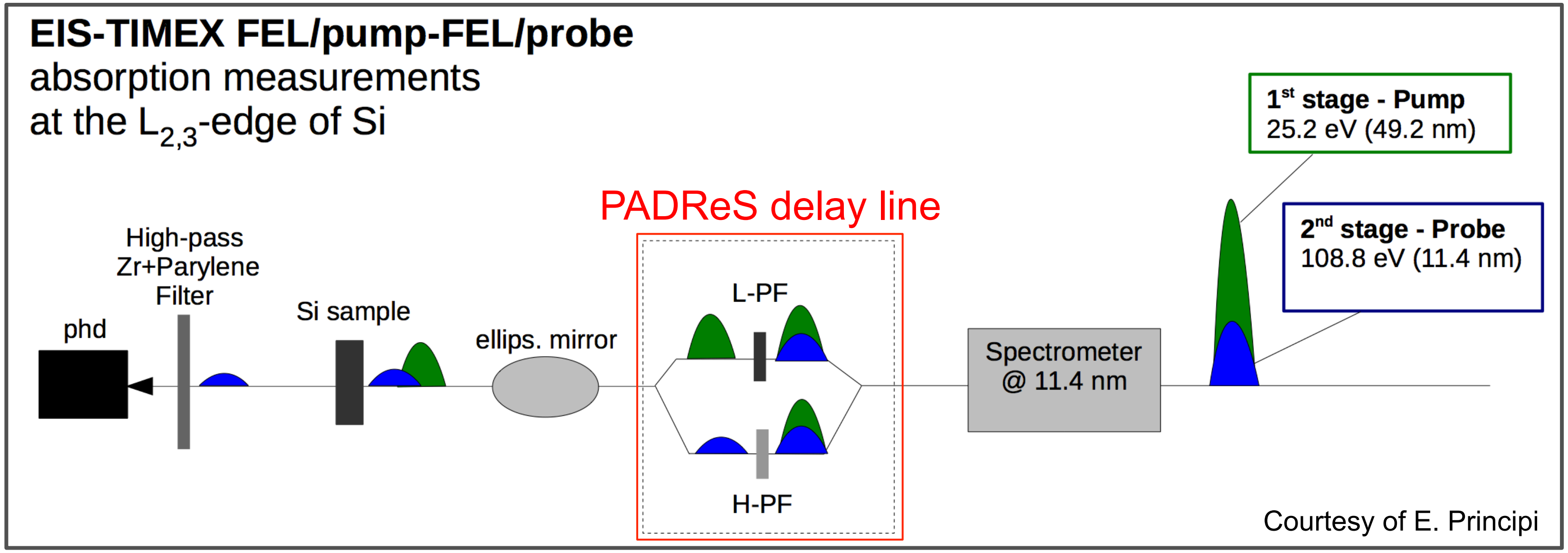
possible applications in FWM

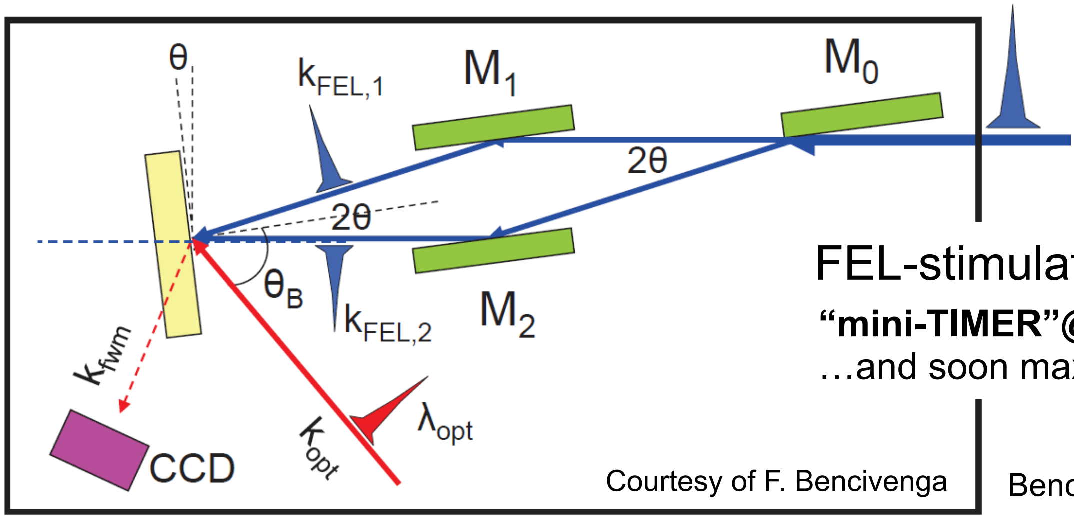
One seed pulse –> two color "zero-delay" FEL pulses using the two-stage FEL2



possible applications in pump-probe experiments (when combined with an appropriate split-and-delay stage)

SPLIT AND DELAY





FEL-stimulated **transient grating**

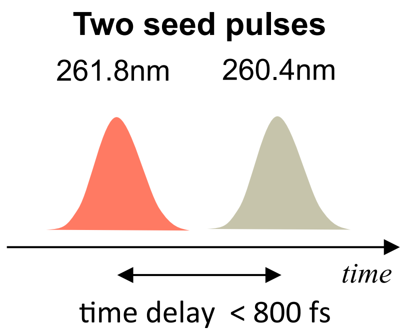
“mini-TIMER”@DiProI

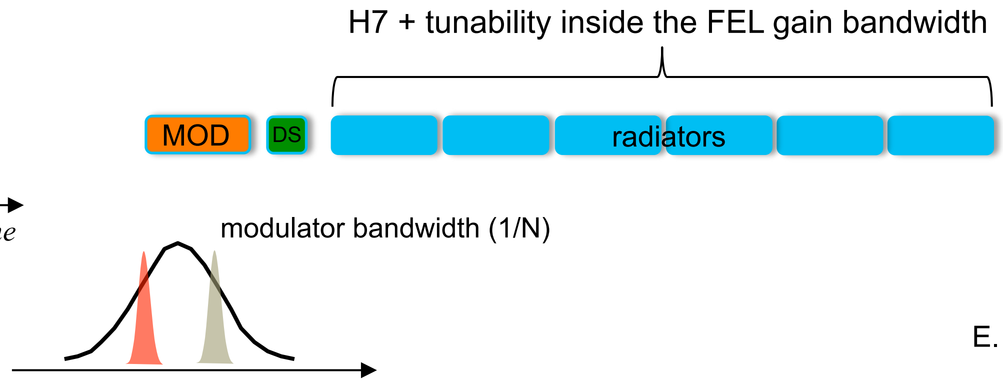
…and soon maxi-TIMER @EIS-TIMER beamline

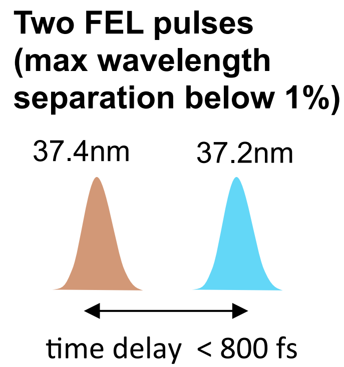
Bencivenga *et al.*, *Nature* 2015

TWO COLOR OPERATION AT THE FERMI SEEDED FEL: TWO SEED PULSES

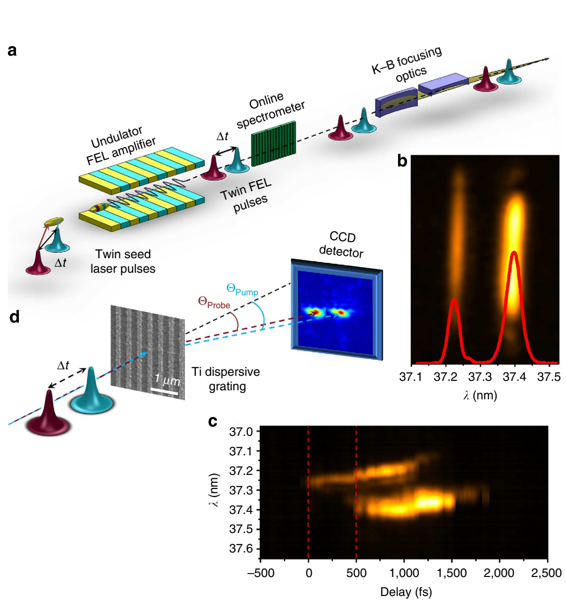
Two color seed pulses –> two color FEL pulses inside the FEL bandwidth

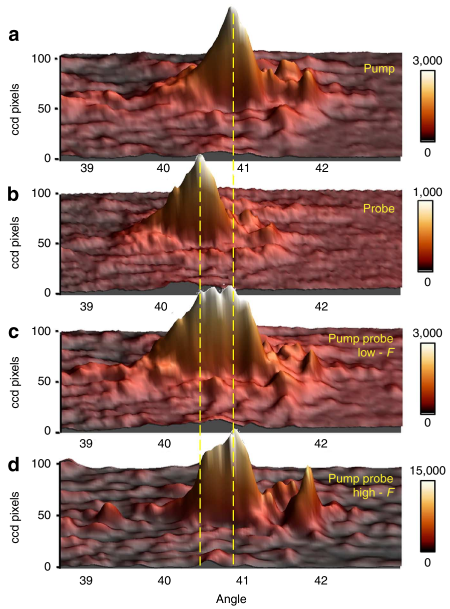






E. Allaria *et al.*, *Nat. Commun.*, 2013



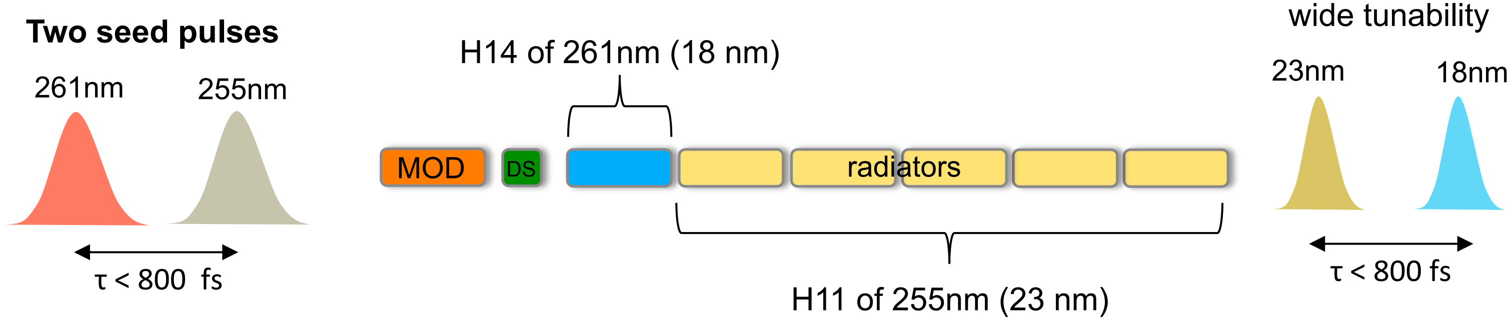


probing structural dynamics in solid samples using diffraction

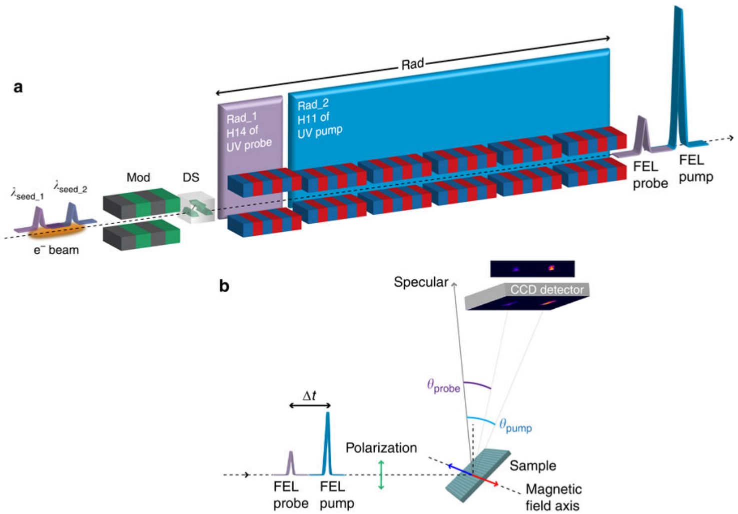
TWO COLOR OPERATION AT THE FERMI SEEDED FEL: TWO SEED PULSES

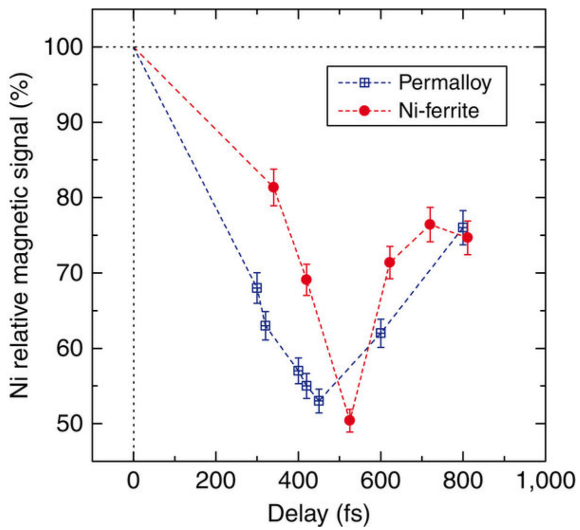
Two color seed pulses –> split undulator scheme

Two FEL pulses



E. Ferrari *et al., Nat. Commun.*, 2016





probing demagnetization dynamics in magnetic compounds

EXOTIC TWO COLOR SCHEMES AND FULL SPECTRO-TEMPORAL SHAPING OF FEL PULSES AT FERMI

BUNCHING IN A SEEDED FEL

Dispersive section strength

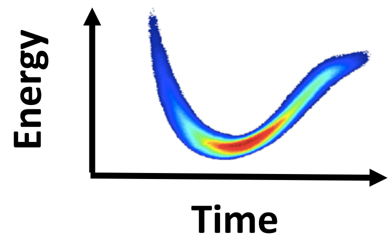
Seed laser envelope

$$b_n(t) \sim J_n[-nBA(t)]\exp\{in[\phi_s(t)+\phi_e(t)]\}$$

Bessel function

Seed phase

Electron energy profile



Bunching envelope	⟷	FEL temporal profile
$\phi_s(t)+\phi_e(t)$	⟷	FEL phase

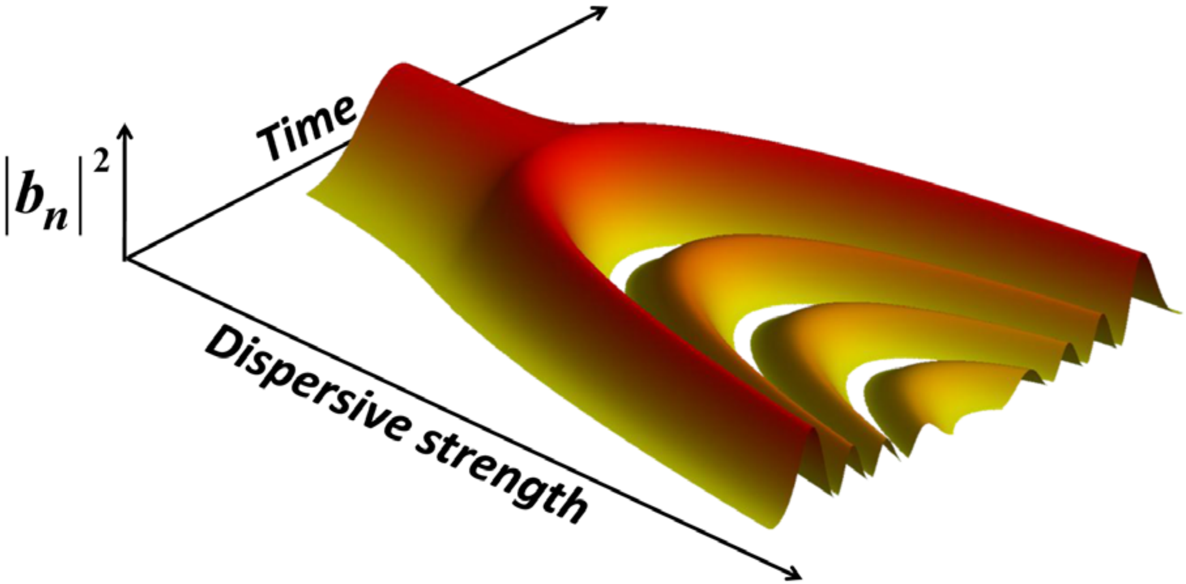
The FEL pulse can be shaped through the manipulation of the seed envelope A(t) and phase $\phi_s(t)$

FEL PULSE ENVELOPE

Bunching at the *nth* harmonic

$$b_n(t) \sim J_n[-nBA(t)] \exp\{in[\phi_s(t) + \phi_e(t)]\}$$

Amplitude profile



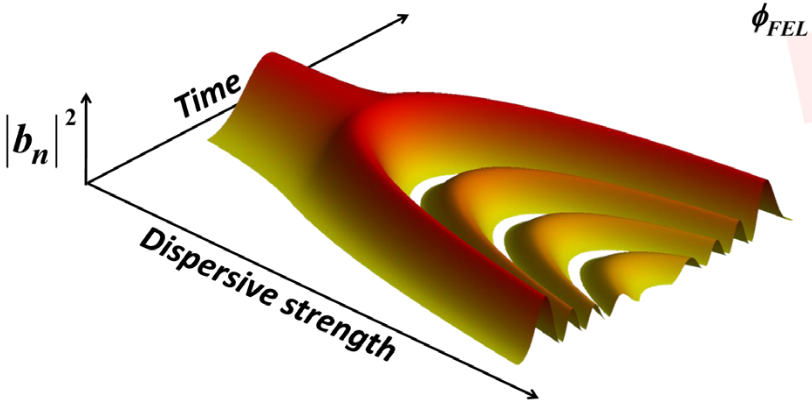
FEL SPECTRUM

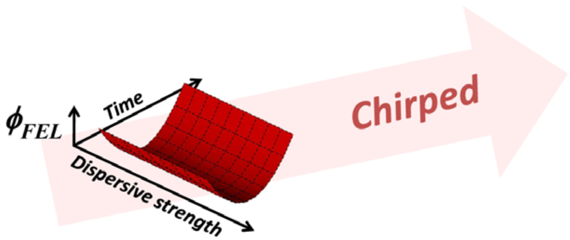
Bunching at the *nth* harmonic

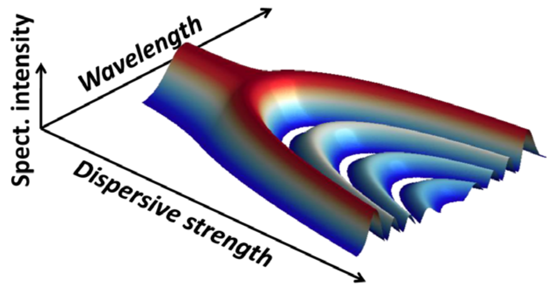
$$b_n(t) \sim J_n[-nBA(t)]\exp\{in[\phi_s(t)+\phi_e(t)]\}$$

Amplitude profile

Phase profile

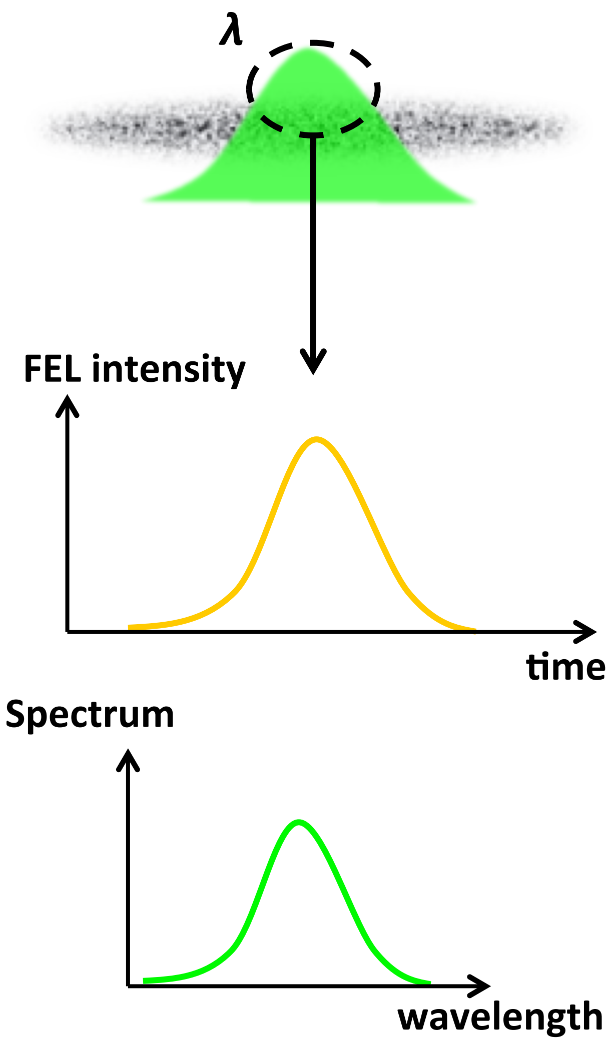




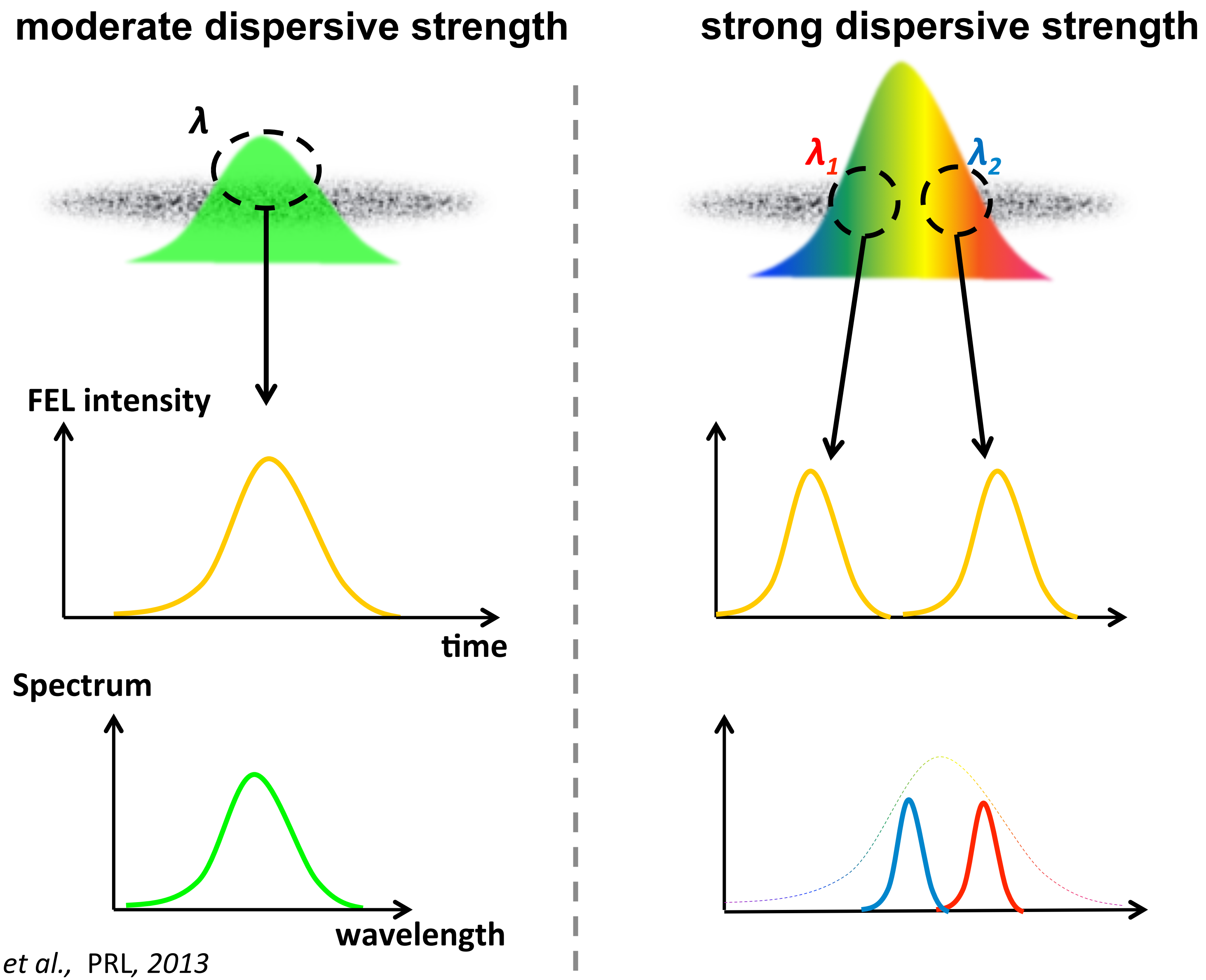


SEEDED FELs AS SELF-STANDING SOURCES FOR X-RAY PUMP – X-RAY PROBE EXPERIMENTS

moderate dispersive strength

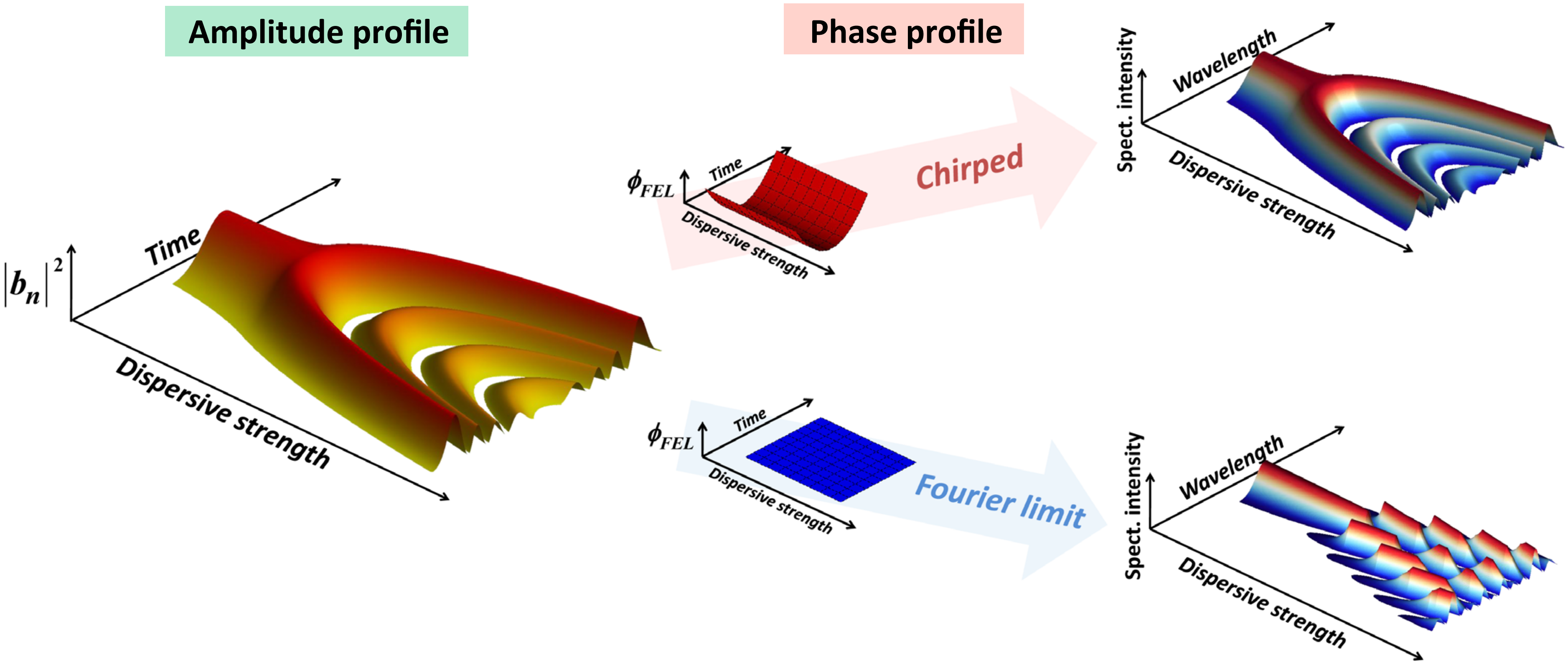


SEEDED FELs AS SELF-STANDING SOURCES FOR X-RAY PUMP – X-RAY PROBE EXPERIMENTS



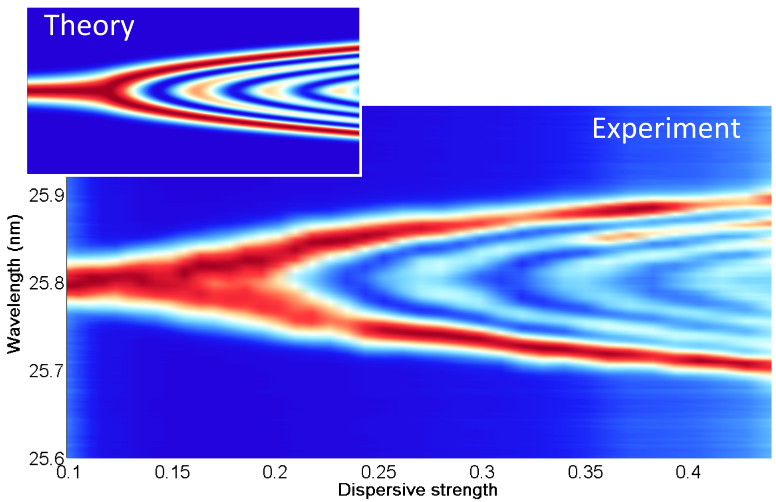
G. De Ninno *et al.*, PRL, *2013*

GENERATION OF TRANSFORM LIMITED FEL PULSES

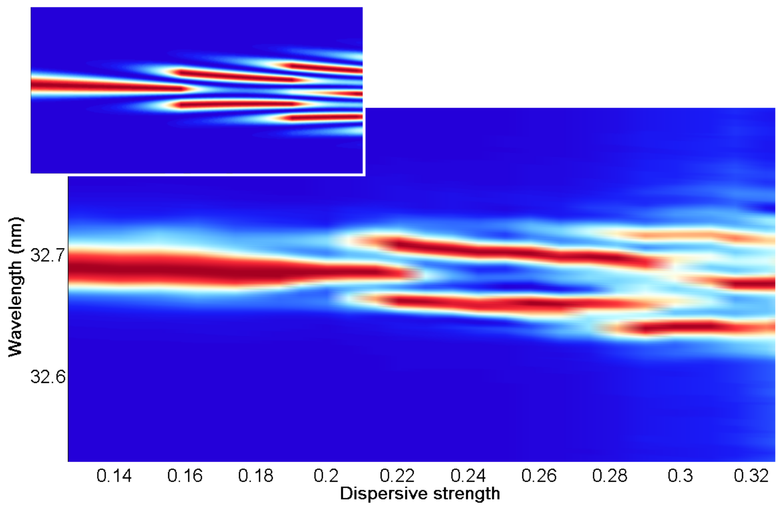


EXPERIMENTAL DEMONSTRATION

Strong chirp



Compensated chirp

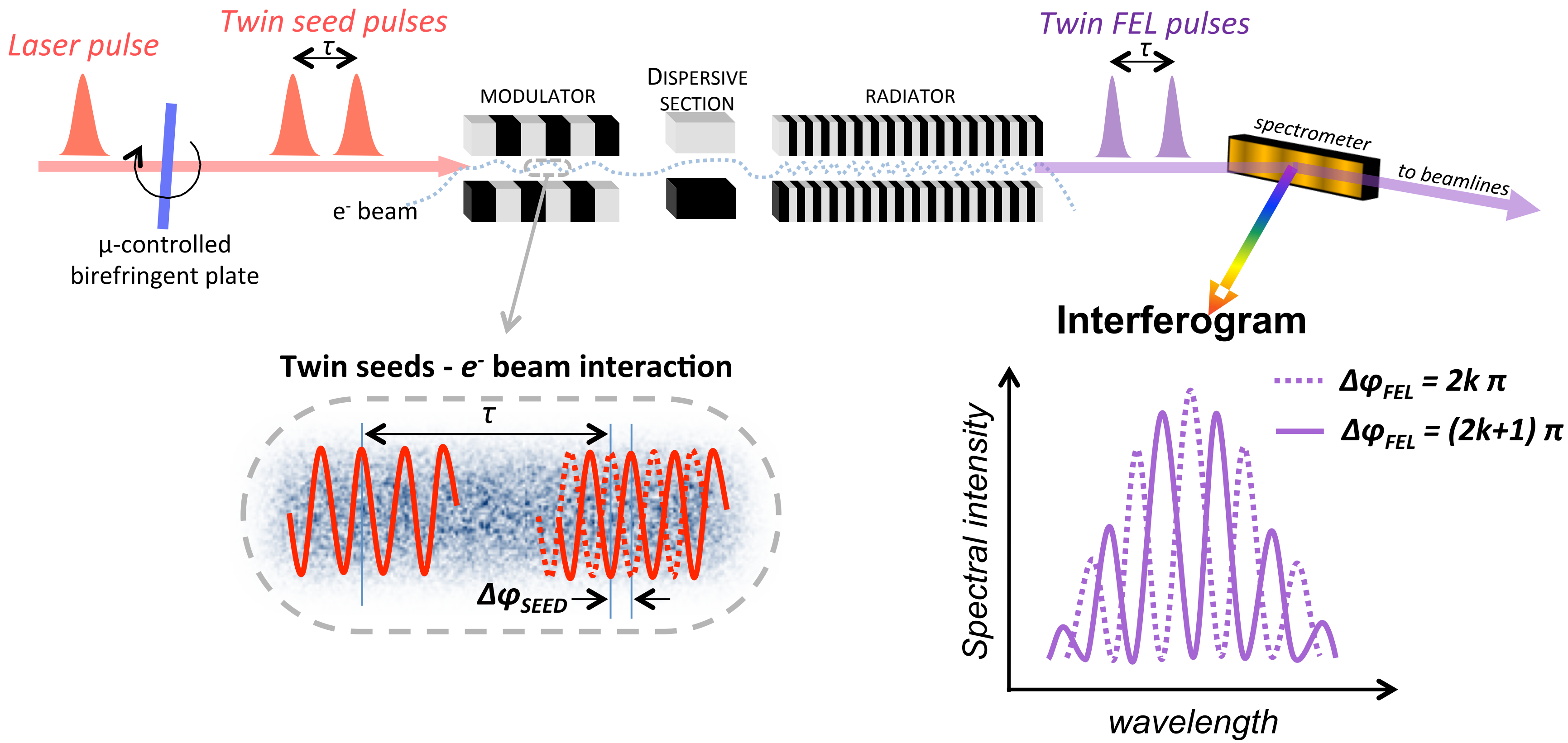


First demonstration of the possibility to generate a transform-limited FEL pulse

Gauthier *et al.*, PRL, 2015

GENERATION OF TIME-DELAYED PHASE-LOCKED PULSES

Two phase-locked seed pulses generate two phase-locked FEL pulses:

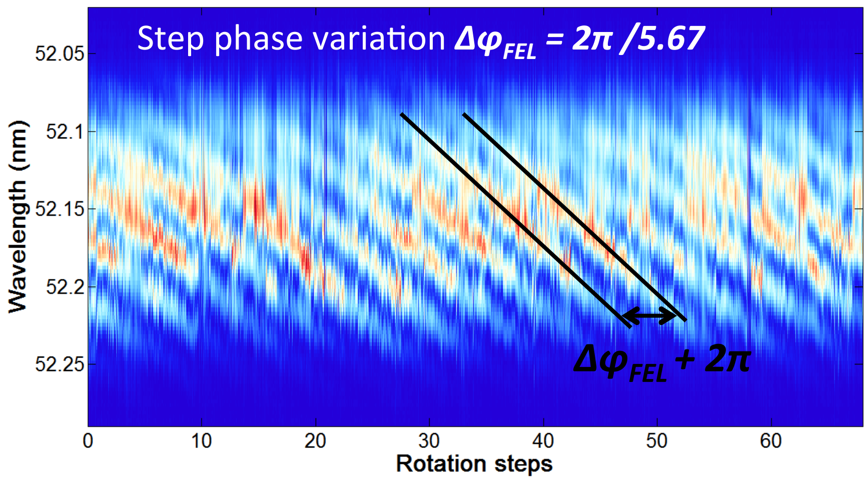


Control the phase difference between the carrier waves of the two time-delayed FEL pulses.

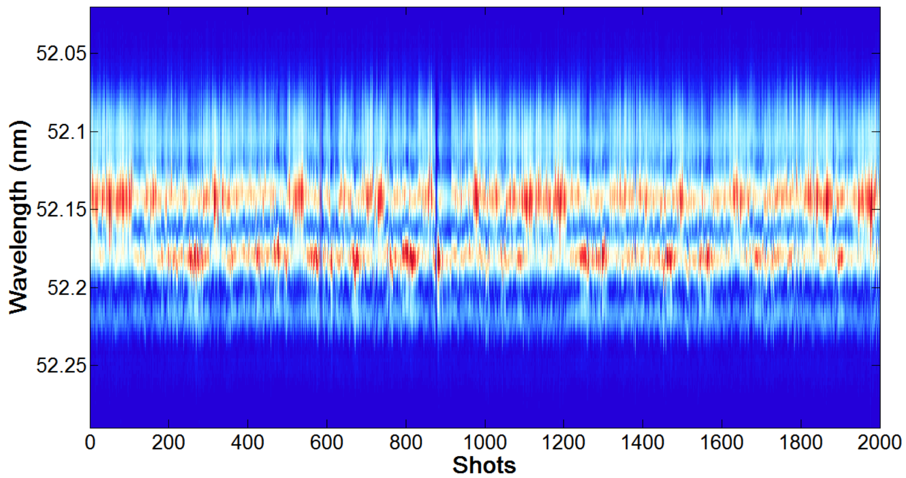
Gauthier *et al.*, PRL, 2016

TIME-DELAYED PHASE-LOCKED PULSES: EXPERIMENTAL RESULTS

Interferograms vs. phase variation



Sequence of single-shot spectra



tuning of the twin-seed phase

⬇

precise control of the twin-FEL phase

phase stability: $\lambda_{FEL}/12$ RMS

⬇

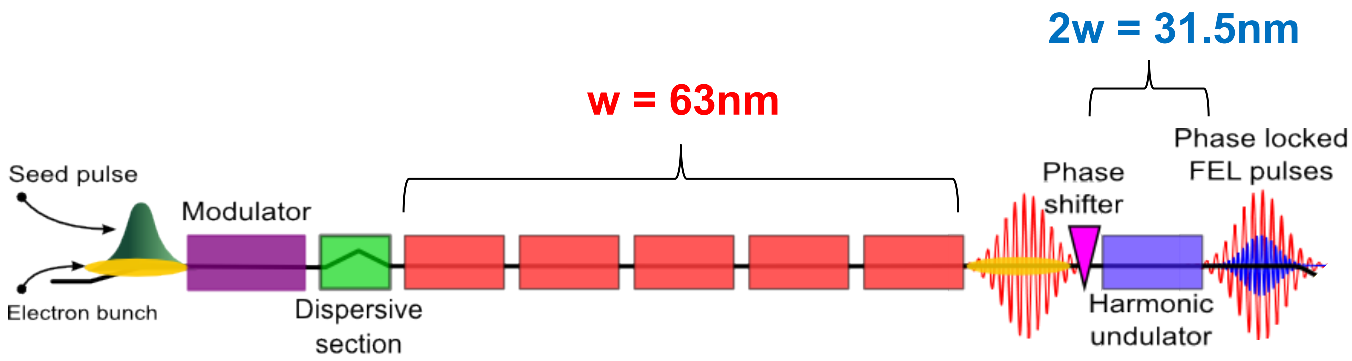
locking in phase better than 15 attoseconds

Possible applications: nonlinear coherent transient interferometry and spectroscopy, spectral holography, quantum state holography, highly resolved spectroscopy, …

Gauthier *et al.*, PRL, 2016

"ZERO-DELAY" PHASE-LOCKED PULSES FOR COHERENT CONTROL

Phase locking between two harmonics of the seed, controlled by means of an electron phase shifter.



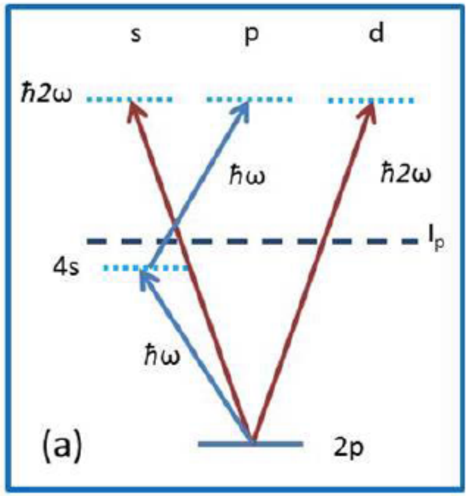
<u>Proof-of-principle experiment</u>:

Two-path quantum interference experiment (Brumer-Shapiro).

Interferences between 2 pathways for Ne ionization:

Ionization of Ne with 1 photon at 2w **vs.** 2 photons at w.

K. C. Prince *et al.*, *Nature Photonics*, 2016

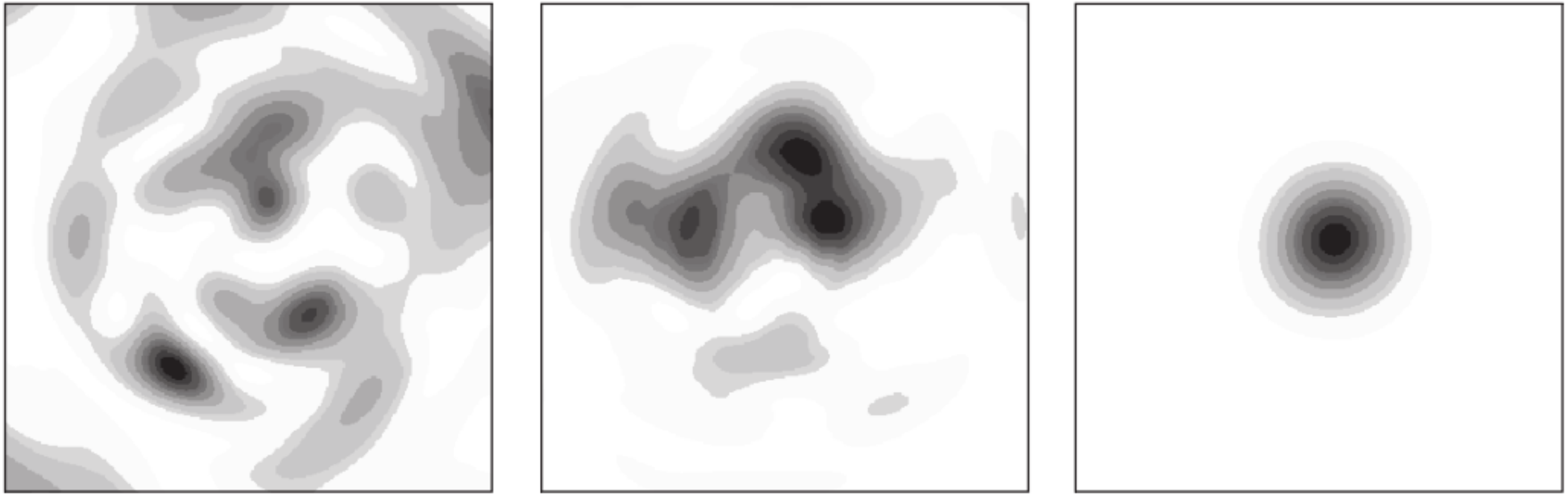


THERE ARE MANY MORE THINGS YOU CAN DO IN THE TEMPORAL DOMAIN BY USING AN EXTERNAL SEED TO TRIGGER THE FEL EMISSION…

BUT LET'S SWITCH TO THE TRANSVERSE PLANE...

FUL DESCRIPTION OF THE FEL RADIATION MECHANISM

3D FEL theory: $$\left(\frac{\partial}{\partial \hat{z}} + i\Delta\hat{\nu} + \frac{\hat{\nabla}_\perp^2}{2i}\right)a_\nu(\hat{\boldsymbol{x}};\hat{z}) = -\int \frac{2\rho d\theta}{2\pi} e^{-i\nu\theta} \int d^2\hat{p} \int d\hat{\eta} f(\theta,\hat{\eta},\hat{\boldsymbol{x}},\hat{\boldsymbol{p}};\hat{s}),$$



At saturation the fundamental (TEM_{00}) mode, which has the highest growth rate, dominates.

E. L. Saldin, E .A. Schneidmiller and M. V. Yurkov, *New J. Phys.,* 2010

ORBITAL ANGULAR MOMENTUM (OAM) OF LIGHT

Optical vortices, i.e., helically phased beams with a field dependence $E \propto e^{im\phi}$, carry orbital angular momentum*

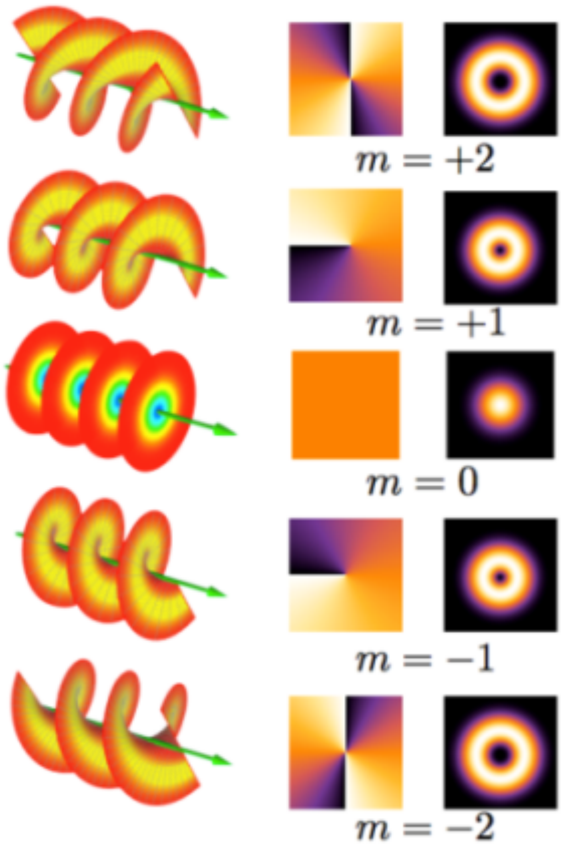


image by Ebrahim Karimi

Classically: $L = \varepsilon_0 \int \mathbf{r} \times (\mathbf{E} \times \mathbf{B})\, d\mathbf{r}$

Analogy with quantum mechanics:

$$L_z = -i\hbar \frac{\partial}{\partial \phi}$$

$$\text{If } \psi \propto e^{im\phi} \Rightarrow \langle L_z \rangle = \hbar m$$

*Allen *et al.*, *Phys. Rev.* A, 1992

SO, WHAT CAN WE DO WITH OPTICAL VORTICES?

Visible wavelengths:

- H. He *et al.*, **Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity**, *Phys. Rev. Lett.* **75**, 826 (1995).
- M. P. J. Lavery *et al.*, **Detection of a Spinning Object Using Light's Orbital Angular Momentum**, *Science* **341**, 537 (2013).
- A. Jesacher *et al.*, **Shadow Effects in Spiral Phase Contrast Microscopy**, *Phys. Rev. Lett.* **94**, 233902 (2005).
- J. Wang *et al.*, **Terabit free-space data transmission employing orbital angular momentum multiplexing**, *Nature Photonics* **6**, 488 (2012).

XUV and X-rays:

- M. van Veenendaal *et al.*, **Prediction of Strong Dichroism Induced by X Rays Carrying Orbital Momentum**, *Phys. Rev. Lett.* **98**, 157401 (2007).
- A. Picón *et al.*, **Photoionization with orbital angular momentum beams**, *Opt. Express* **18**, 3660 (2010).
- A. S. Rury *et al.*, **Examining resonant inelastic spontaneous scattering of classical Laguerre-Gauss beams from molecules**, *Phys. Rev.* A **87**, 043408 (2013).

HOW CAN WE GENERATE OAM?

Using optical elements, e.g., a spiral phase plate:

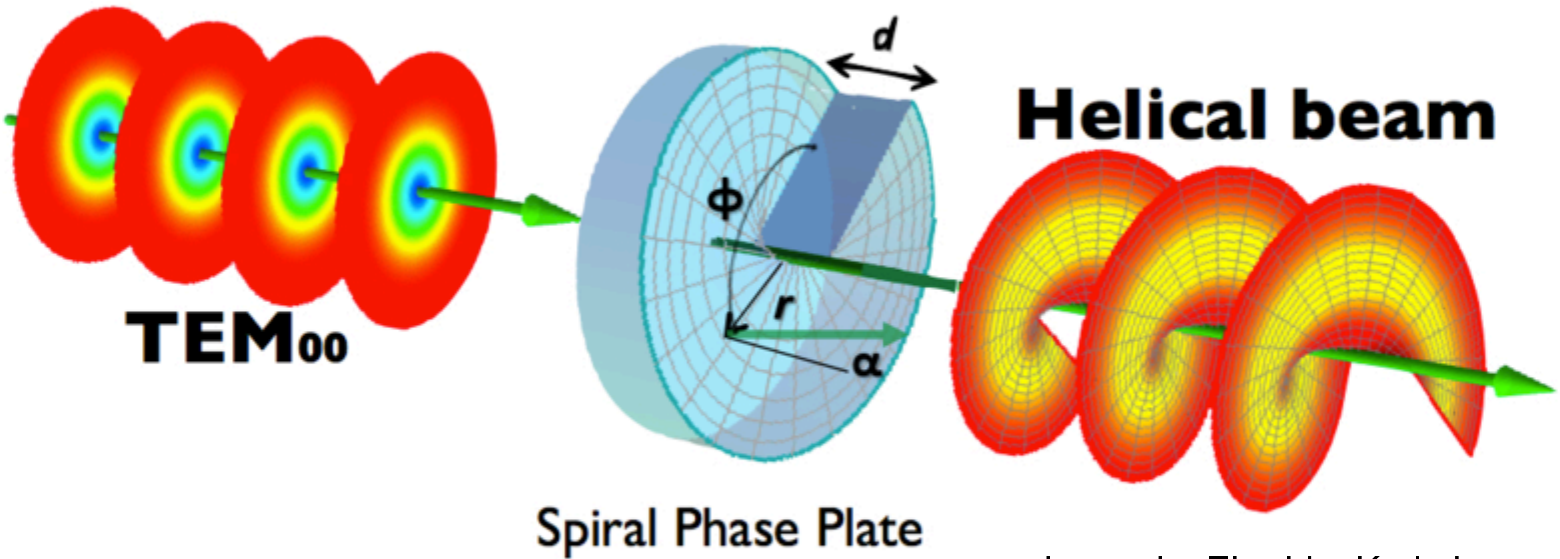
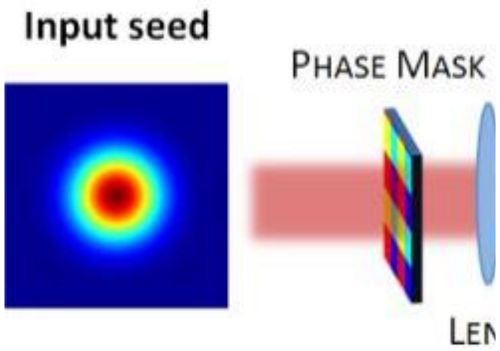


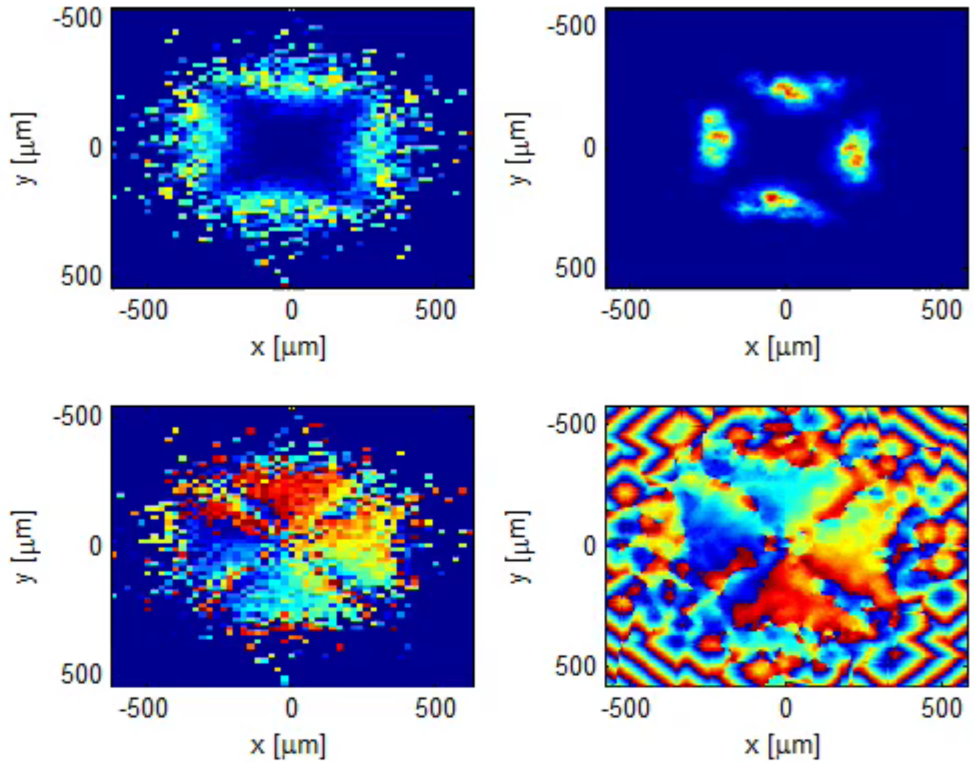
image by Ebrahim Karimi

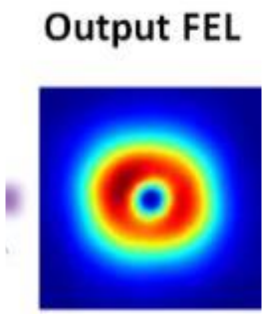
Not practical at XUV and X-ray wavelengths and FEL intensities $\Longrightarrow$ *in situ* generation preferred

WHAT CAN WE DO AT FERMI?

Use a phase-mas … **:**

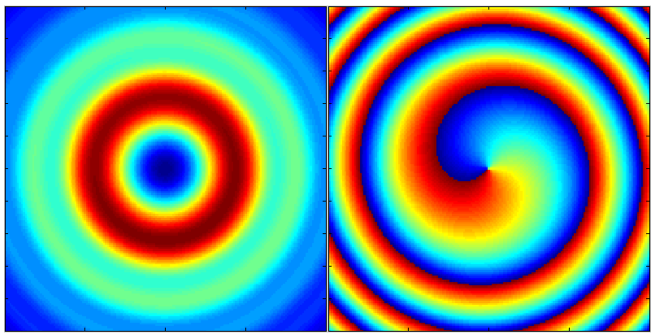


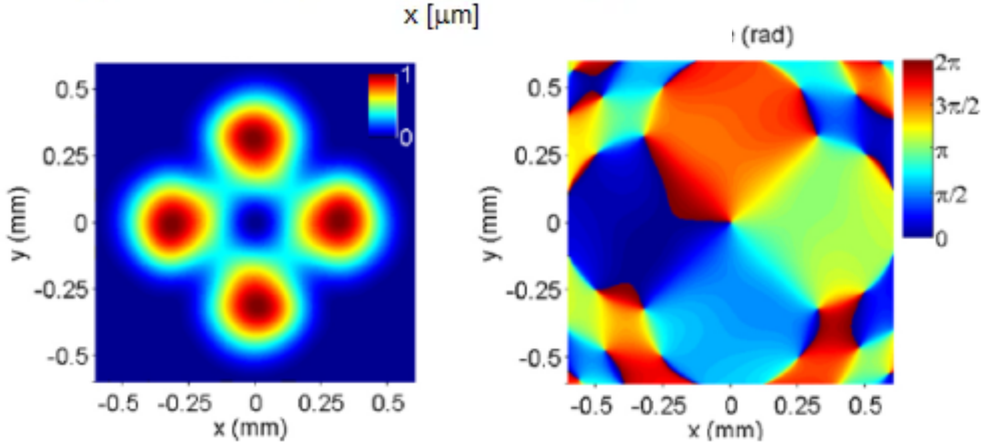




-like phase

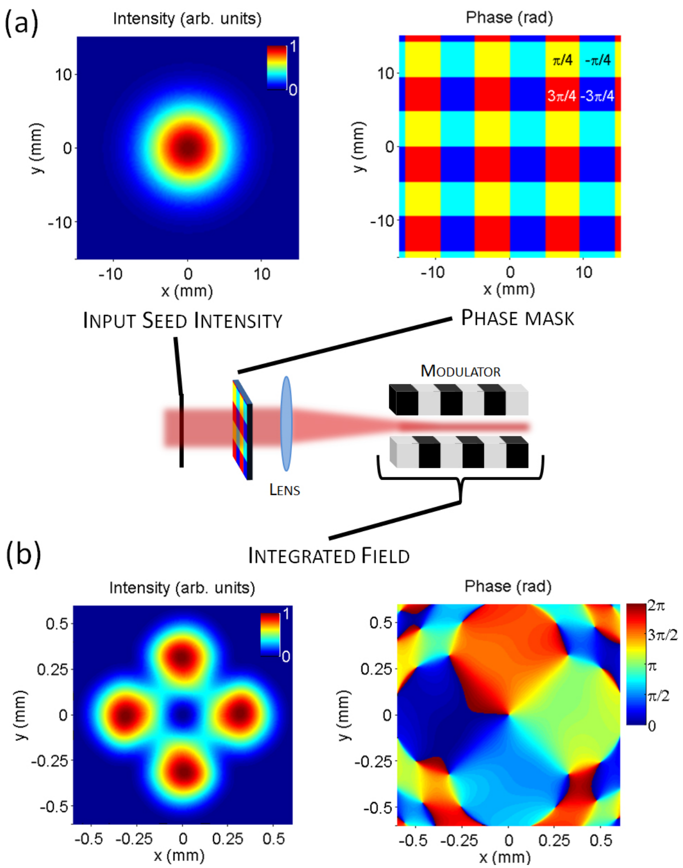
Use a spiral phase p
mask? It doesn‘t wo



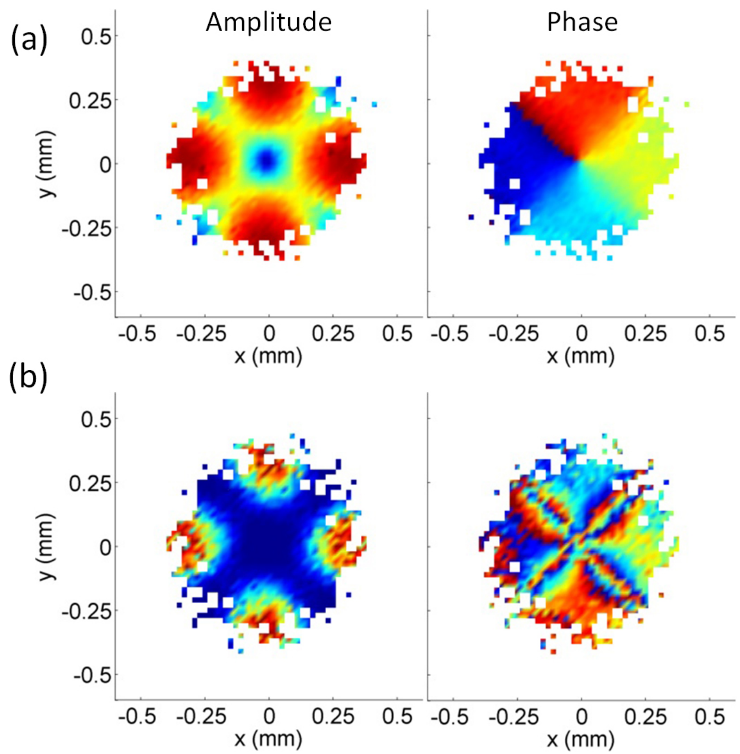


MICROBUNCHING CONSTRUCTION IN THE MODULATOR

Modification of the transverse seed profile using a phase mask:

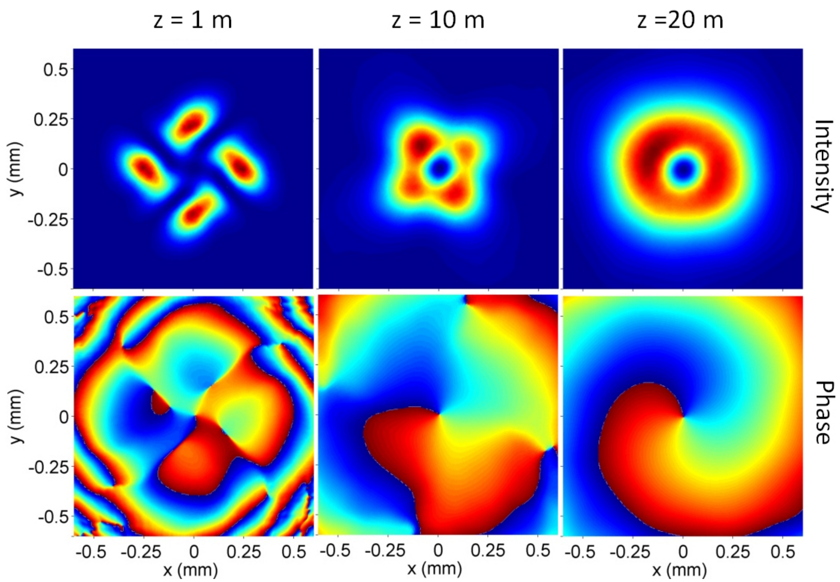


Formation of microbunching in the modulator: transverse profile at a) the fundamental (260 nm) and b) 7th harmonic (37 nm)

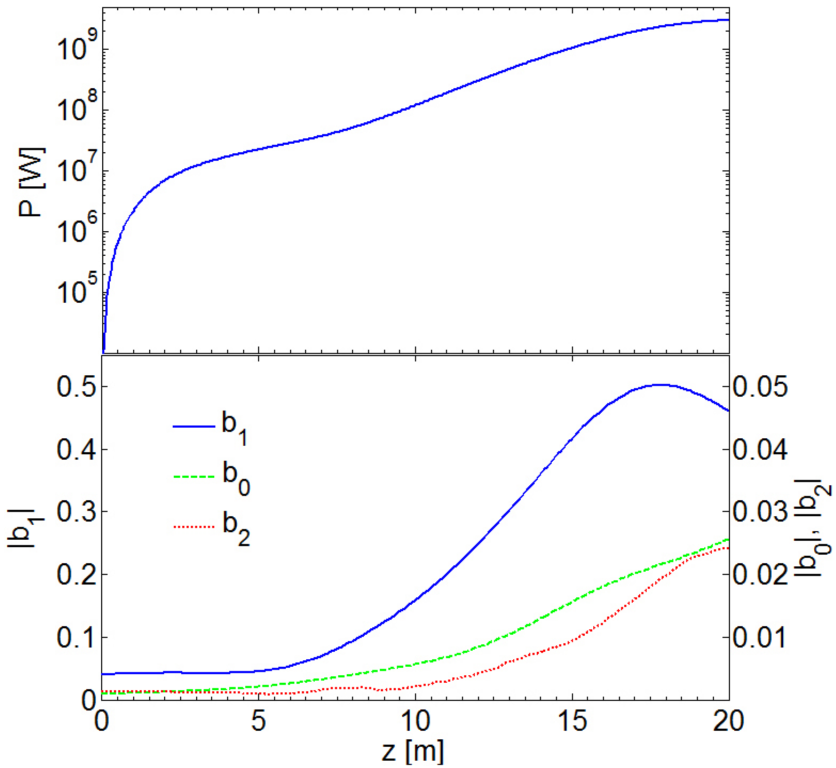


EVOLUTION OF THE RADIATION PROFILE

Transverse radiation profile in the undulator (7th harmonic)



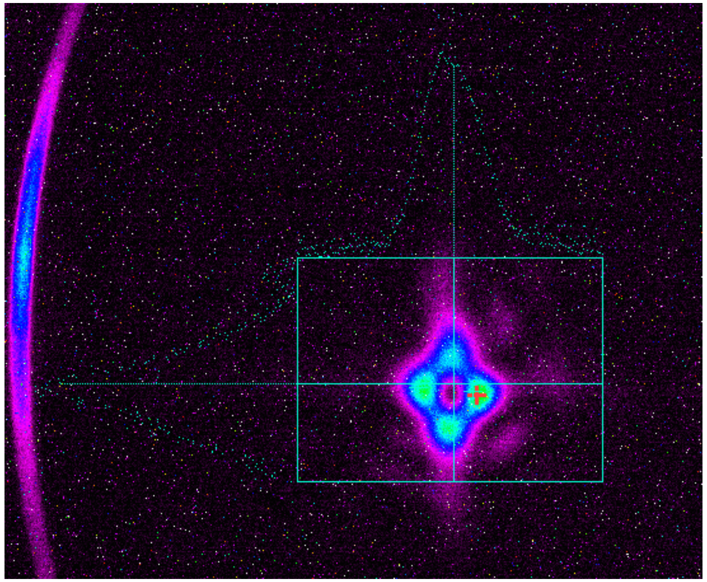
Evolution of the FEL power and bunching factors (I_{beam} = 1 kA, P_{seed} = 1 GW, normalized emittance = 5 x 10^{-6} m)



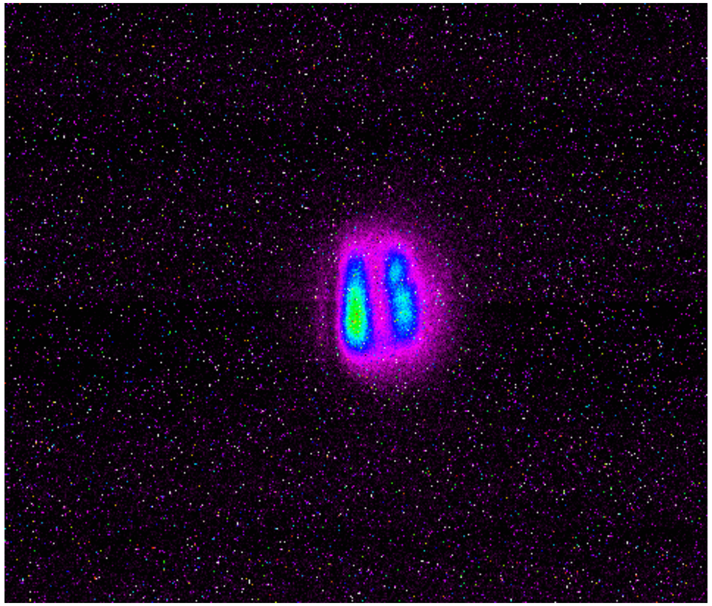
P.R. Ribič *et al.*, PRL 112, 2014

EXPERIMENTAL (ALMOST) DEMONSTRATION

seed transverse intensity profile



FEL intensity profile



Shaping FEL radiation in the transverse plane is much more difficult compared to shaping in the temporal domain!

WHAT HAVE WE JUST LEARNED?

- compared to synchrotrons FELs produce more poweful (orders of magnitude higher peak brilliance) and shorter (femtosecond) pulses with laser-like properties
- self seeding and HGHG improve FEL performance (spectral brightness, central wavelength and pulse energy stability)
- different schemes for SASE and seeded FELs can deliver two color pulses with tunable properties for pump-probe experiments
- HGHG offers full control over the spectro-temporal and spatial properties of FEL light

Acknowledgements:

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FERMI comissioning team
Giorgio Margaritondo, EPFL