Coherent Harmonic Generation using the ELETTRA storage-ring optical klystron

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Outline

- Principle and theoretical framework

CHG induced by the FEL

- Q-switching operation mode → radiation at 220 nm (third harmonic of FEL at 660 nm)

- Energy, temporal and spectral characterization

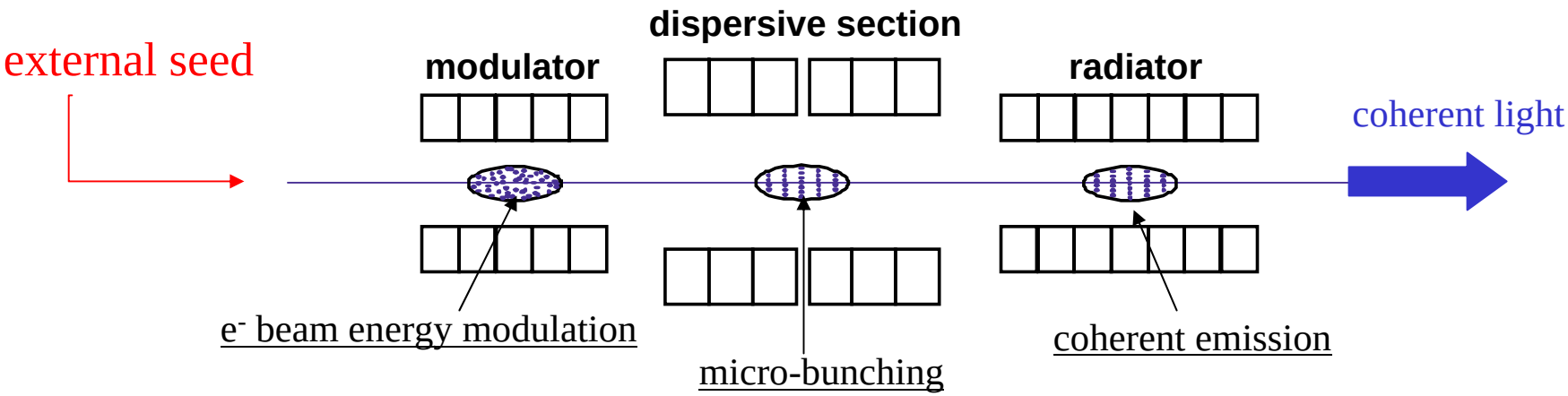
- Comparison with theory

CHG using an external seed

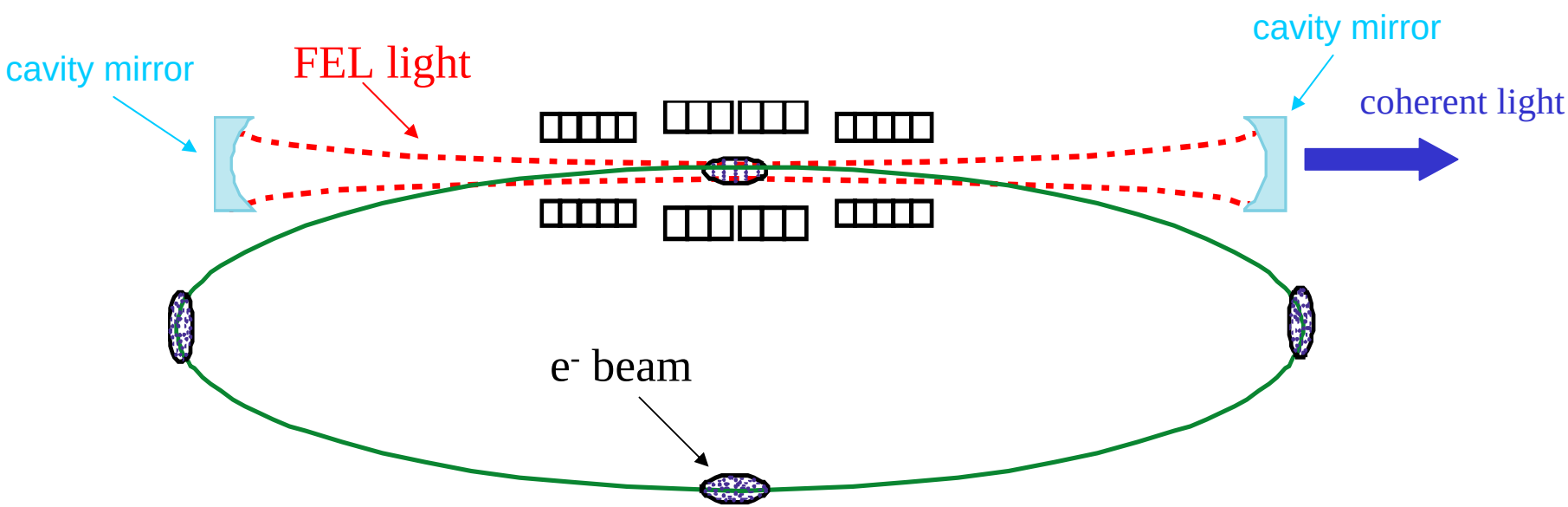
- Time dependent and time independent simulations

- Conclusions and Perspectives

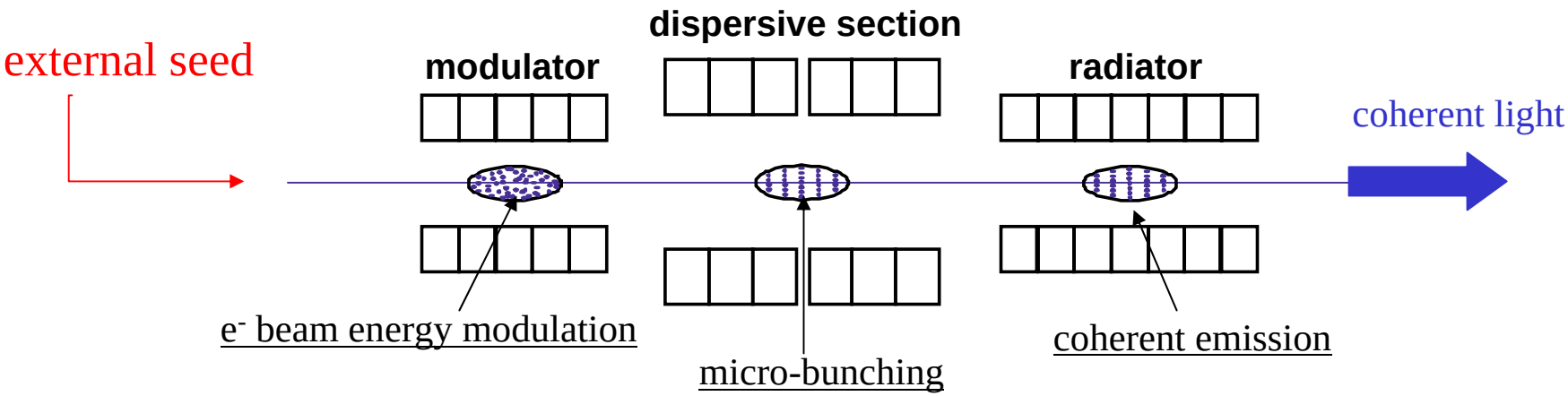
The principle



CHG on a storage ring



The principle



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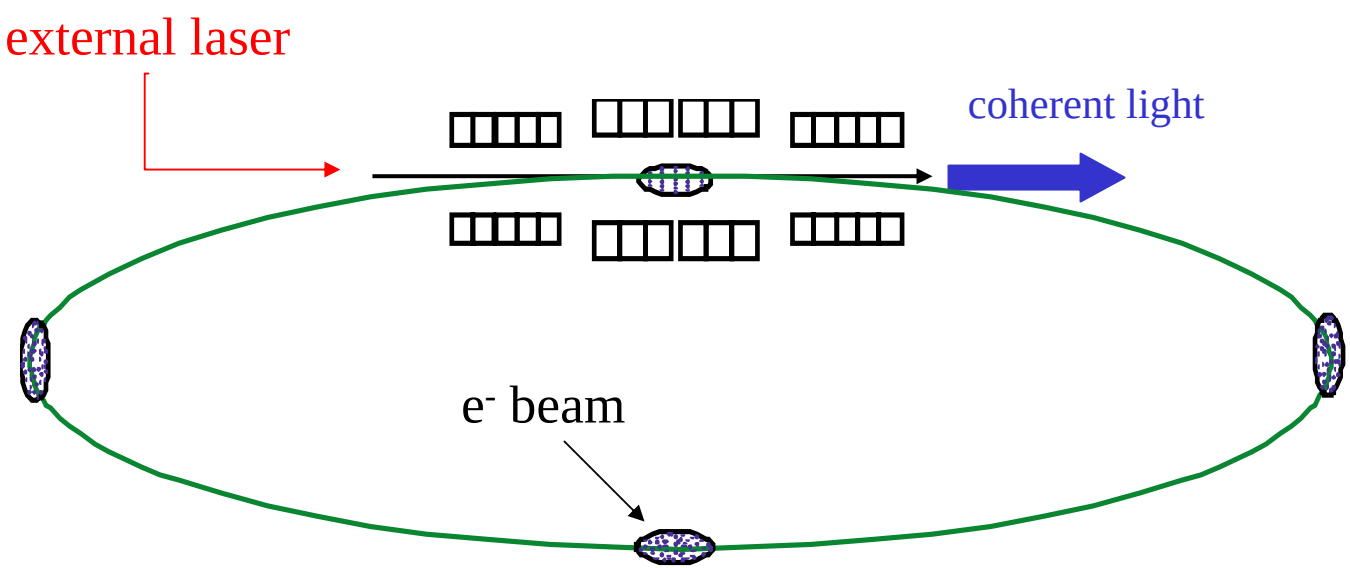


Theoretical framework

The **longitudinal dynamics inside each undulator** is studied by solving the system:

phase of the *j-th* electron

n-th harmonic component of the optical field

$$\frac{d^2\varsigma_j}{d\tau^2} = |a_n| \cdot \cos(\varsigma_j + \phi_n)$$

$$\frac{da_n}{d\tau} = -2\pi \cdot g_{0,n} \cdot \langle e^{-in\varsigma} \rangle$$

small signal gain

Bunching coefficient

$$g_{0,n} \propto \left(\frac{N}{\gamma}\right)^3 \frac{(\lambda_u \cdot K)^2}{\Sigma} I_{peak}$$

$$\langle e^{-in\varsigma} \rangle = \frac{1}{N_p} \sum_{j=1}^{N_p} \left(\cos(n\varsigma_j) + i\sin(n\varsigma_j)\right)$$

Extracted power on the *n-th* harmonic is maximized optimizing the bunching coefficient:

this can be done via a proper tuning of the beam energy and dispersive section strength

Theoretical framework

When HG is performed on a storage-ring FEL, the system

$$\frac{d\varsigma_j}{d\tau} = \nu_j \qquad \left[\nu_j \approx \frac{\gamma_j - \gamma_r}{\gamma_r}\right]$$

$$\frac{d\nu_j}{d\tau} = |a_n| \cdot \cos\left(\varsigma_j + \phi_n\right)$$

$$\frac{da_n}{d\tau} = -2\pi \cdot g_{0,n} \cdot \left\langle e^{-in\varsigma} \right\rangle$$

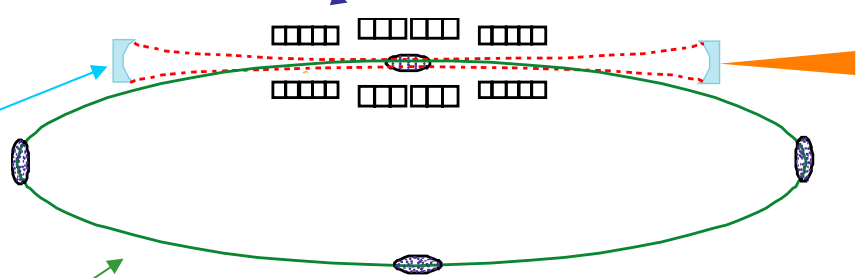
System evolution inside the optical klystron

has to be "closed" by the two equations:

FEL evolution in the optical cavity

$$(a_n)_{new} = (a_n)_{old}\sqrt{1-T_n} + (a_n)_0$$

If external seed

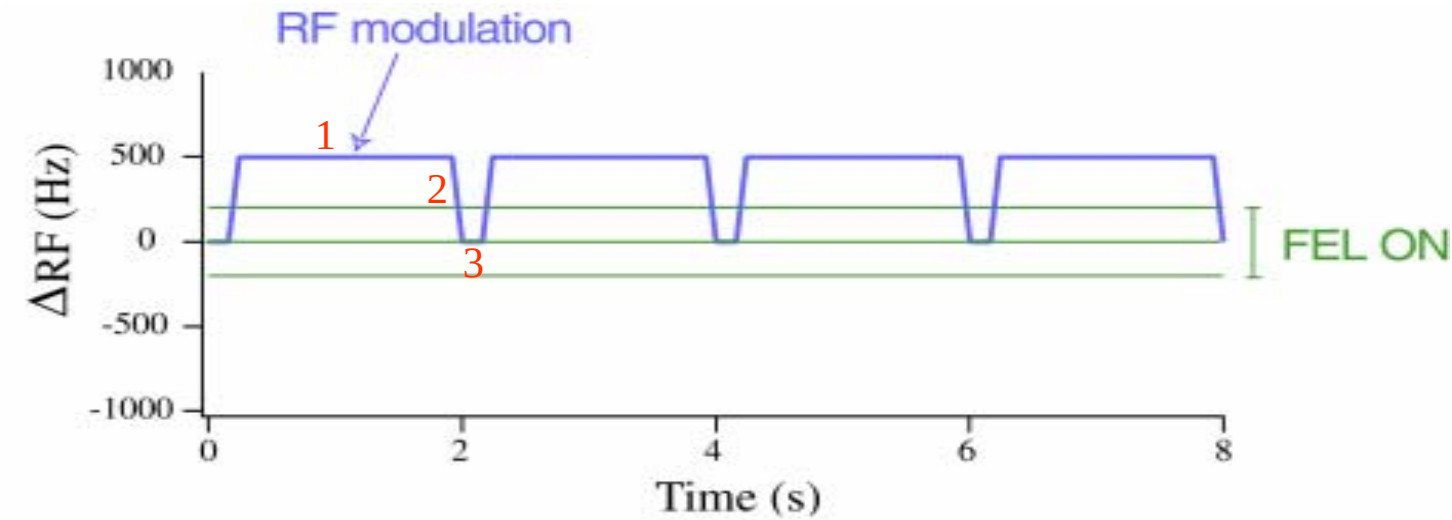


e- beam dynamics in the ring

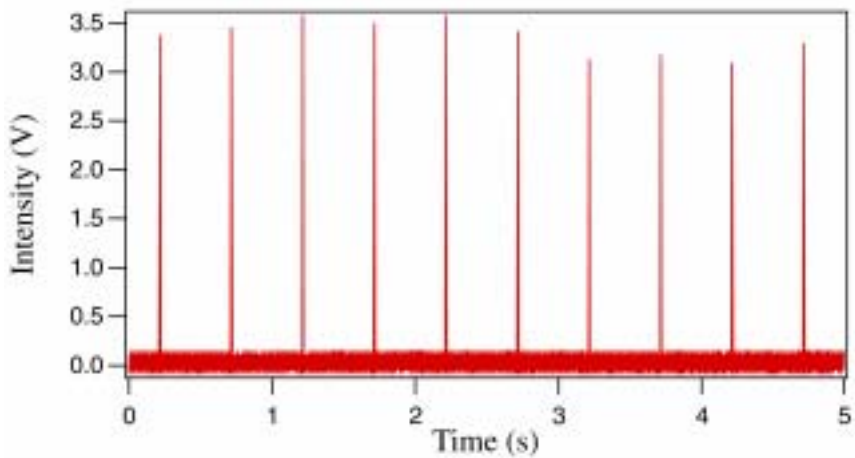
$$(\sigma_\nu)^2_{new} = (\sigma_\nu)^2_{old} - \frac{2T}{\tau_s}\left[(\sigma_\nu)^2_{old} - (\sigma_\nu)^2_0\right]$$

CHG induced by the FEL

Q-switching technique



"Giant" pulses

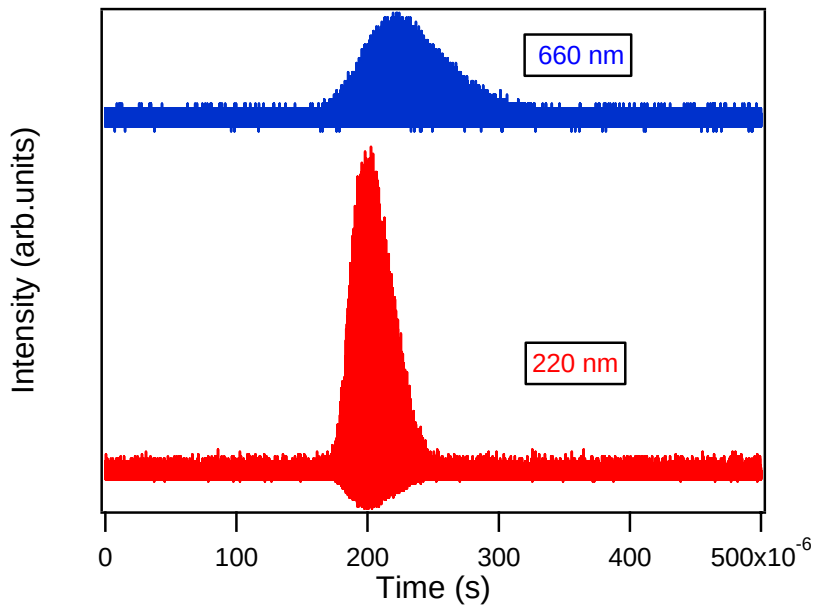


Experimental parameters

FEL (Q-switching mode)	
Beam energy	900 MeV
Total current (4 bunches)	25 mA (max)
Fundamental wavelength	660 nm
Intra-cavity peak power (fund.)	~100 MW
Third harmonic wavelength	220 nm
Repetition rate	2-10 Hz
Optical Klystron	
Number of undulator periods	18
Undulator period	10 cm

Signal intensity

Intensity as a function of time

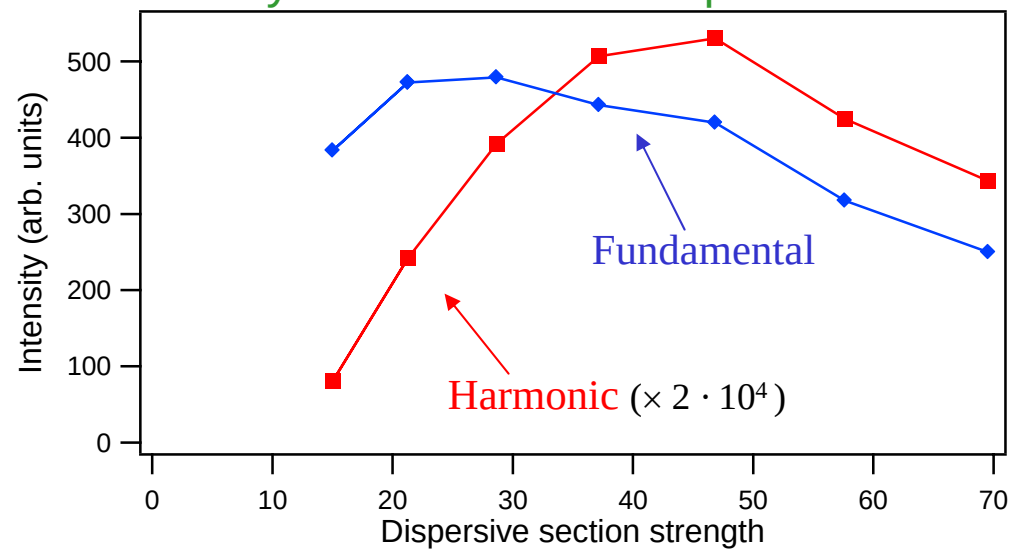


- Harmonic signal risetime is about a factor 3 shorter than fundamental

- Harmonic signal is about a factor 25 above spontaneous emission

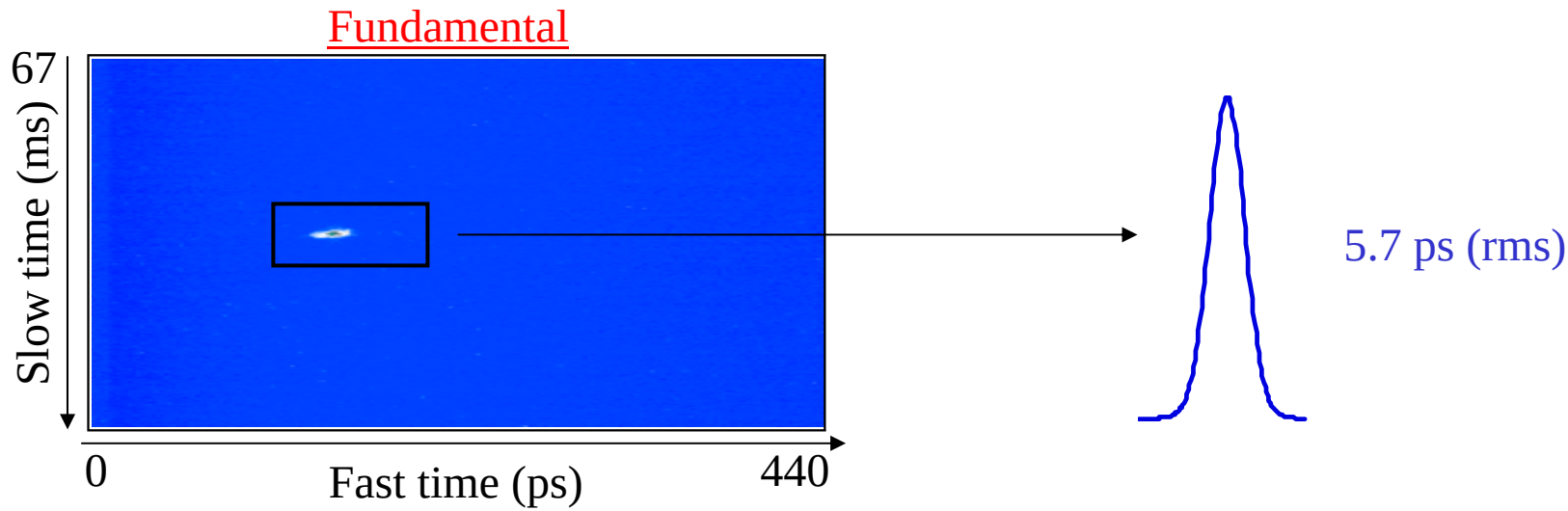
→ Micro-pulse energy: 0.1-0.5 nJ

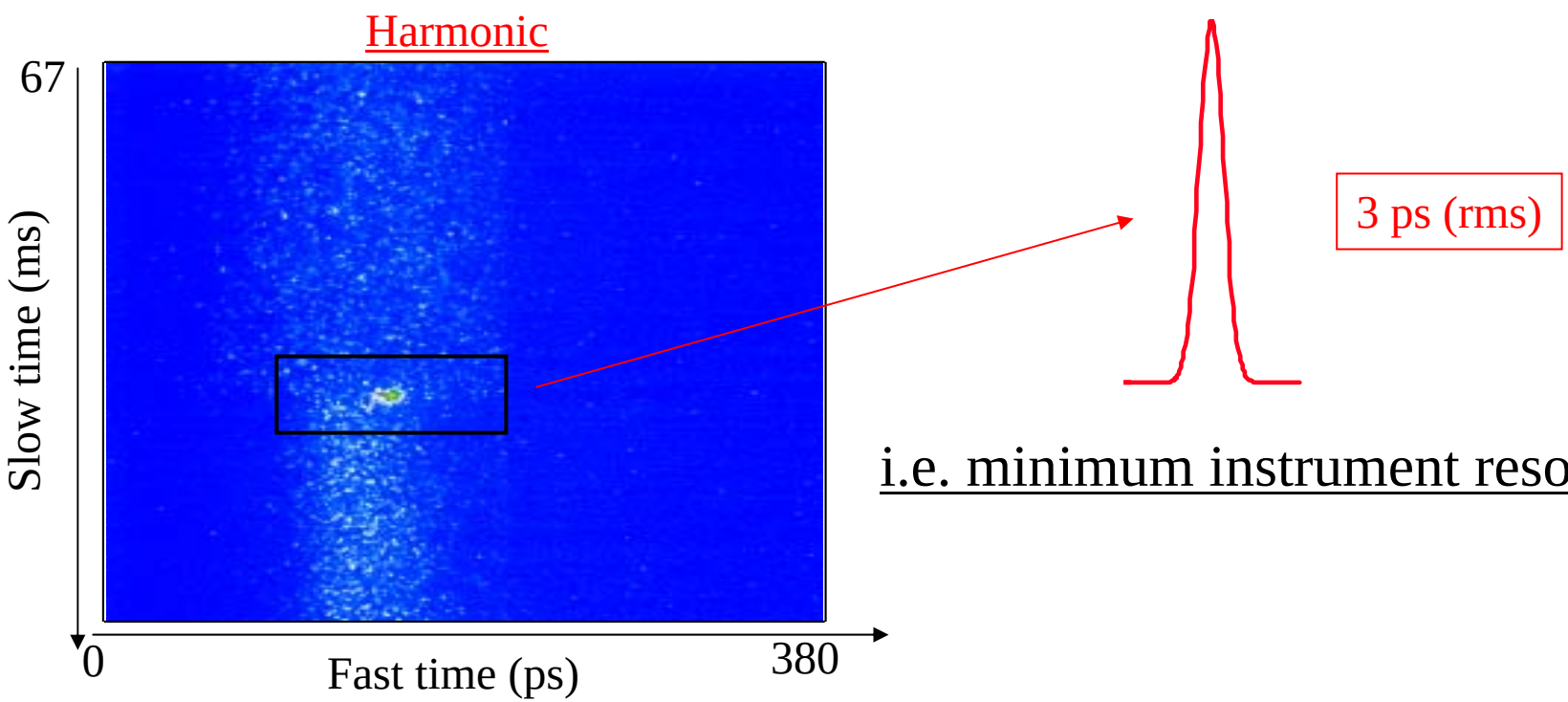
Intensity as a function of dispersive section



-There is an “optimized” value of dispersive section strength above which the harmonic signal is reduced

Temporal characterization (streak camera)



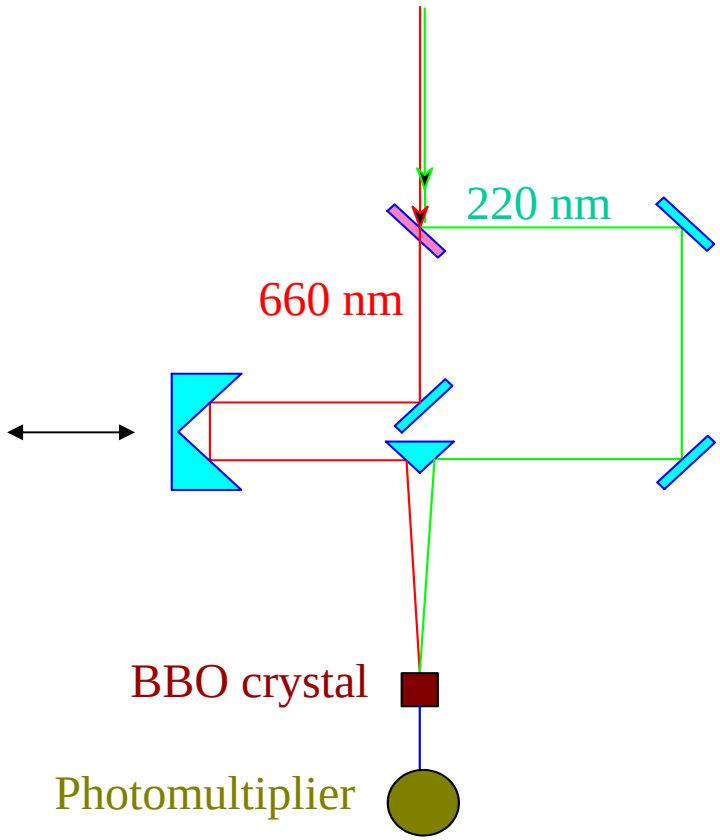


i.e. minimum instrument resolution !!

Temporal characterization (cross-correlation)

Background-free cross-correlation (660+220 nm)
using a **BBO crystal**.
Phase matching at ~ 60 deg.

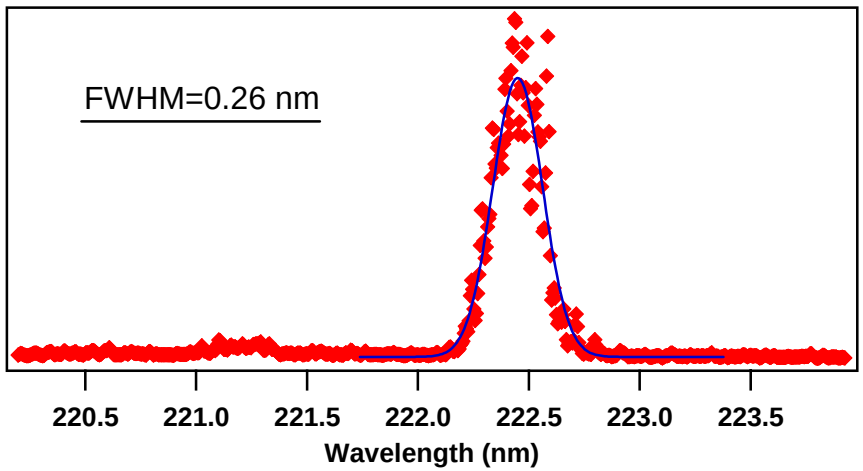
Signal from the optical cavity:
660+220 nm



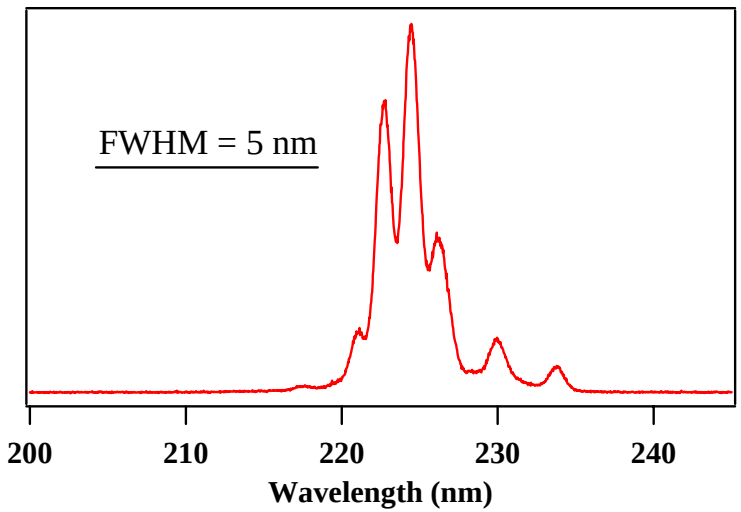
With 5 mJ at 660 nm and
1 nJ at 220 nm
One should get about
0.1 nJ at 330 nm

Spectral characterization

Harmonic spectrum (scanning mode)



Spontaneous emission from the Optical Klystron

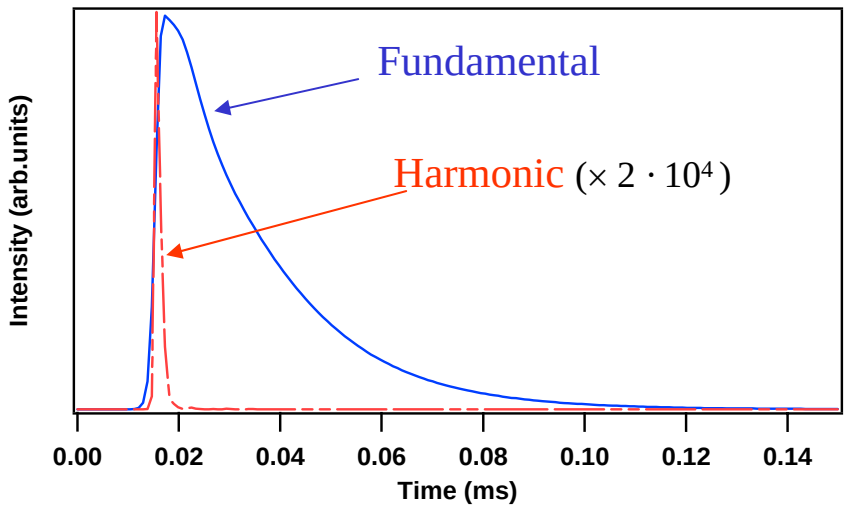


Comparison with theory

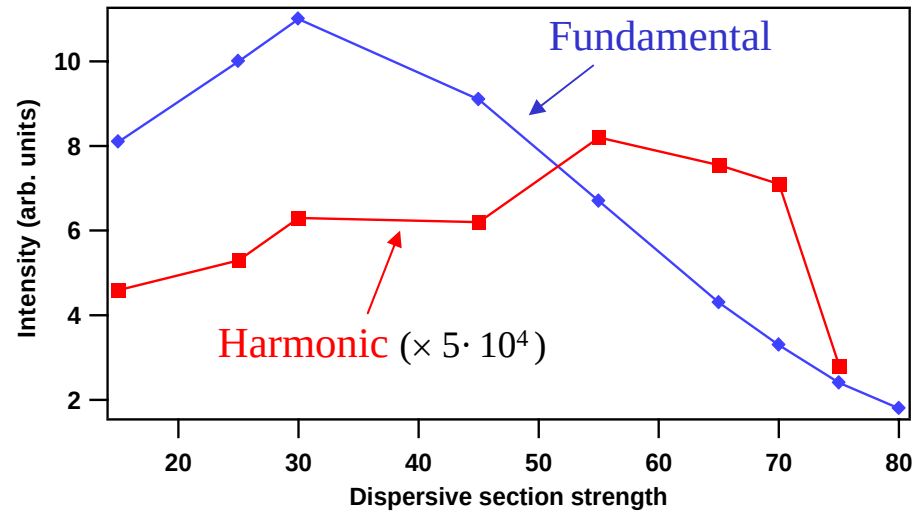
Theoretical model implemented in PERSEO

Simulations are in good agreement with experiments

Intensity as a function of time



Intensity as a function of dispersive section



Micro-pulse peak power

	Fundamental (W)	Harmonic (W)
Experimental	$8.6 \cdot 10^5$	17.1
Simulated	$6.7 \cdot 10^5$	16.4

(I=20 mA)

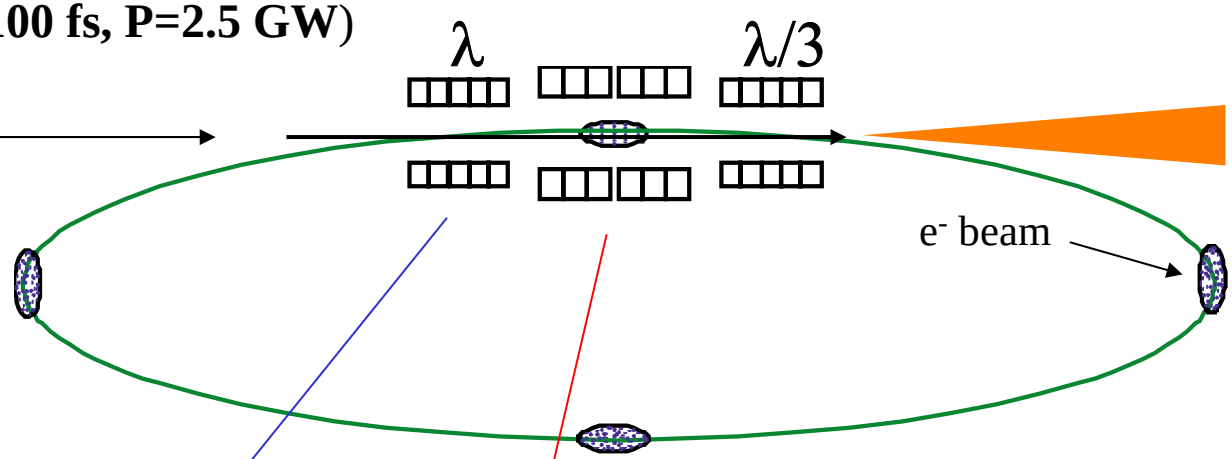
assuming σ = 3 ps

CHG using an external seed

Layout and simulations

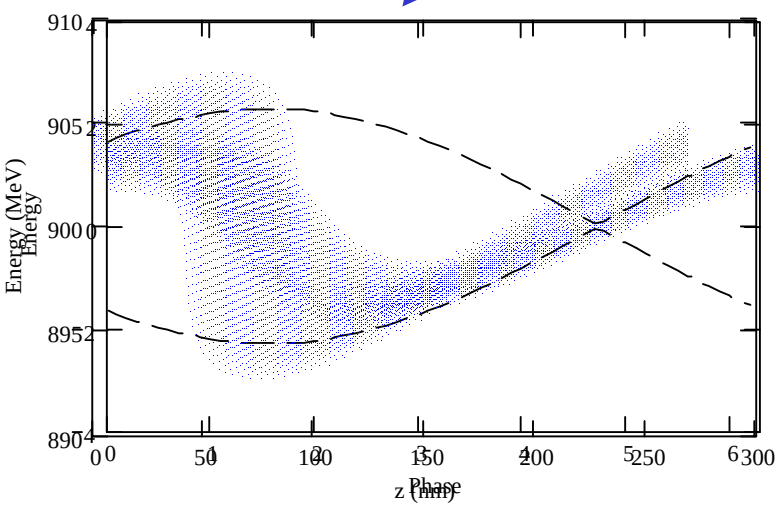
Ti:Sa system

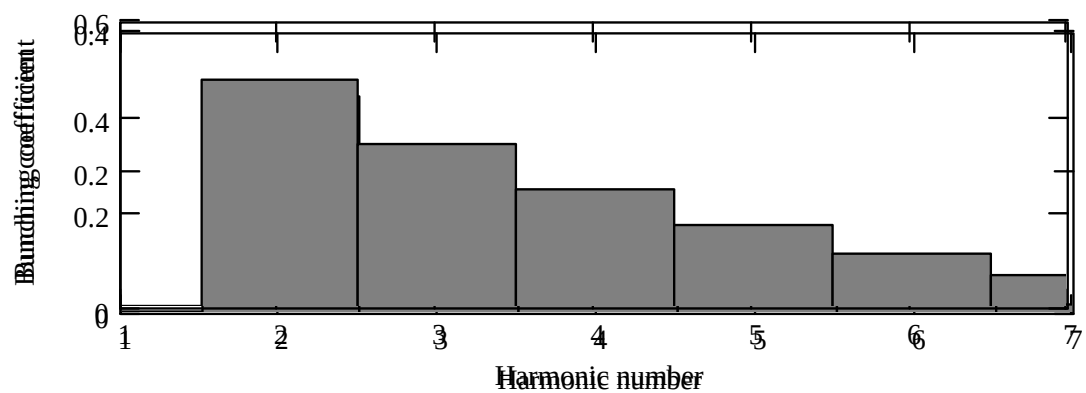
(λ=260 nm, σ_t=100 fs, P=2.5 GW)



Modulator

Dispersive section

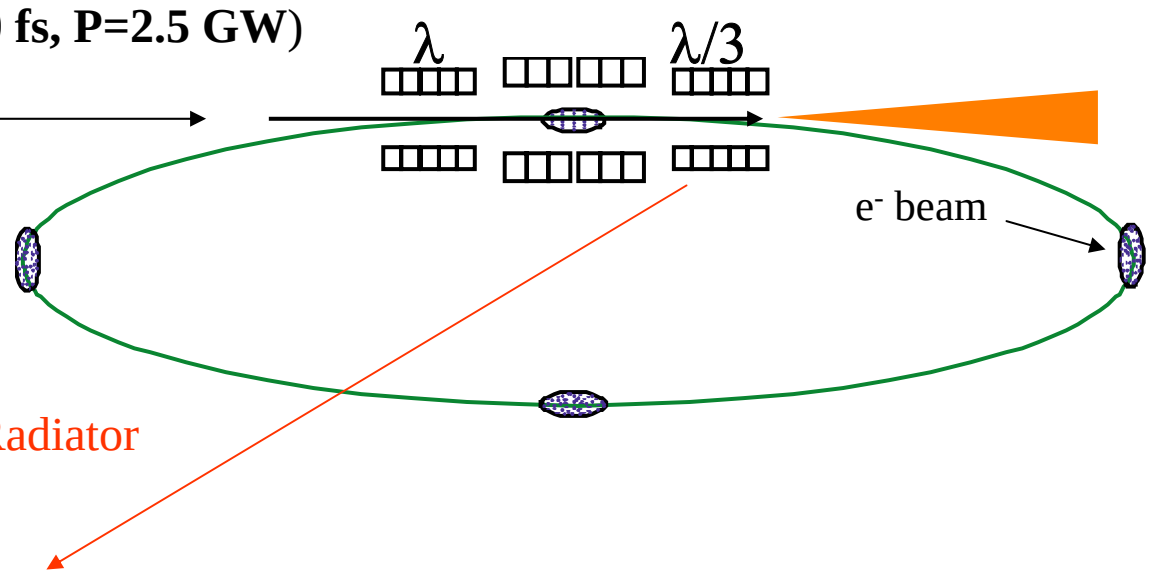




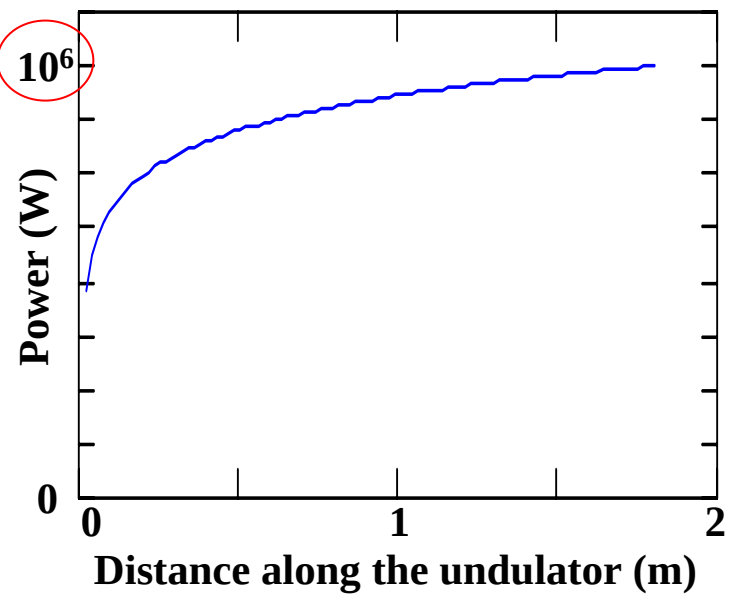
Harmonic radiation

Ti:Sa system

(λ=260 nm, σ_t=100 fs, P=2.5 GW)



Evolution of the harmonic signal



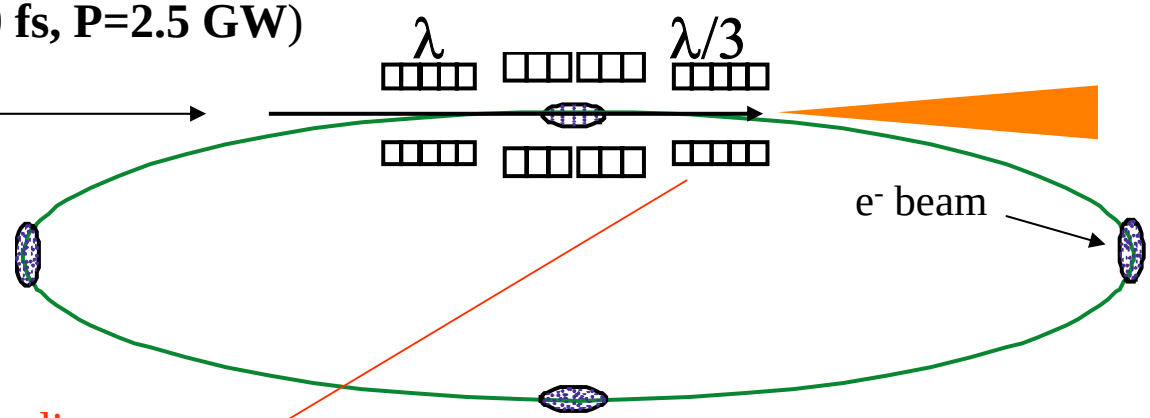
~1 MW output signal at ~ 90 nm for an input seed of 2.5 GW

~Tuning at λ/5 (~ 52 nm) one gets about 0.1 MW

Harmonic radiation

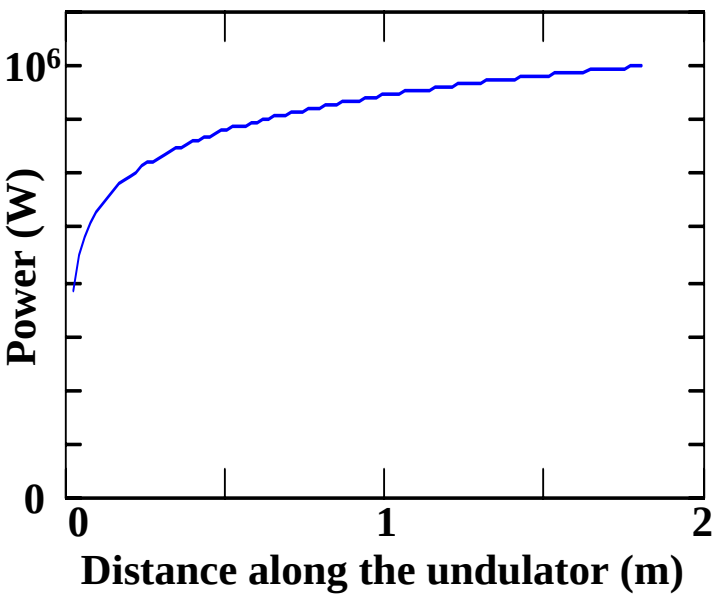
Ti:Sa system

(λ=260 nm, σ_t=100 fs, P=2.5 GW)

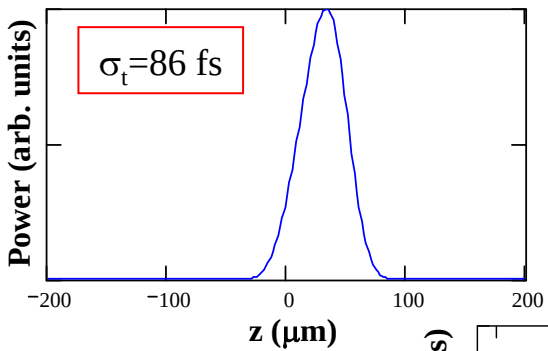


Radiator

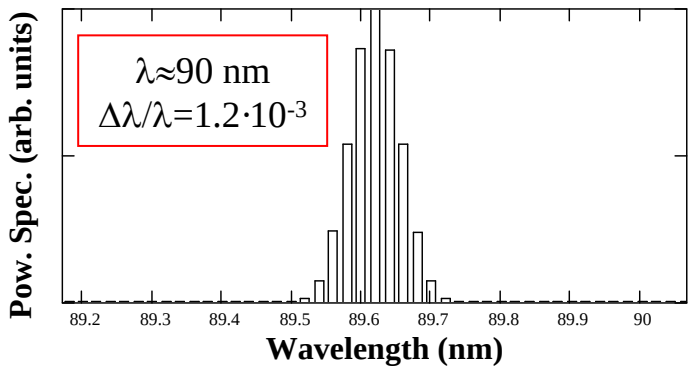
Evolution of the harmonic signal



Pulse profile



Spectrum profile



Conclusions and Perspectives

CHG induced by the FEL

- **Experiment feasibility**: radiation at 220 nm (third harmonic of FEL at 660 nm)

- **Signal characterization**: energy, duration, spectral width

- **Development of a numerical model**: results in good agreement with experiments

- **CHG in the VUV**

- **Direct measurement of the pulse duration**

CHG using an external (Ti:Sa) laser

- **Time-dependent simulations** using PERSEO

Wavelength (nm)	90, 50, 40
Peak power (W)	10^6, 10^5, 10^4
Pulse duration (fs)	90
Repetition rate (Hz)	10-100
Spectral width	Same as the seed pulse

→ **attractive, ready-to-use test facility for CHG**