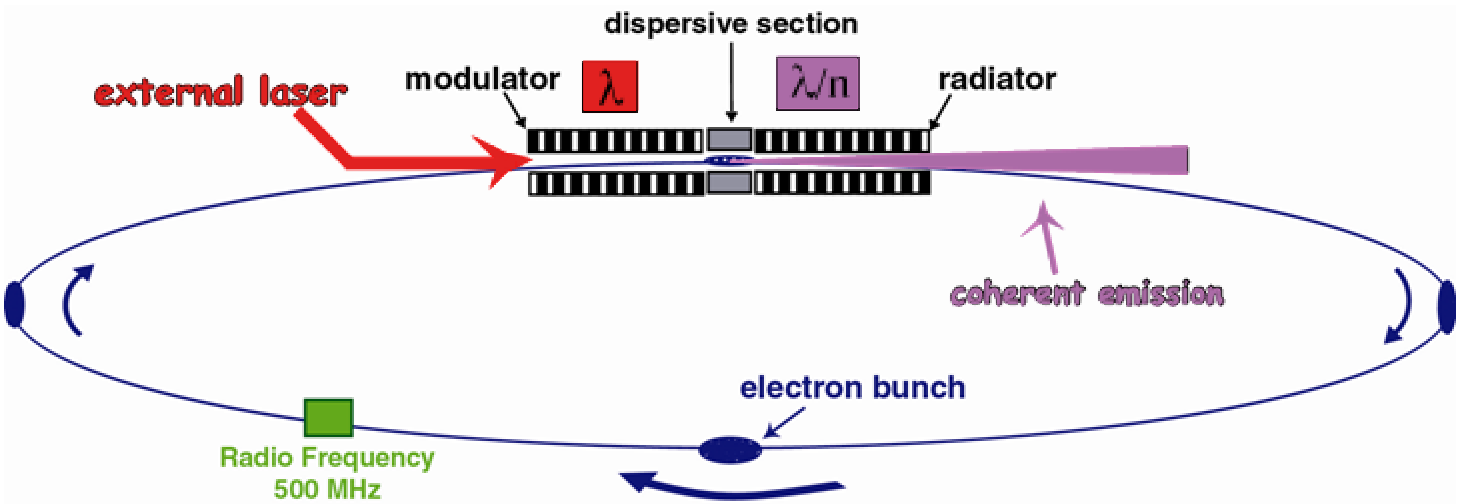
The Elettra Storage Ring FEL: a source for FEL studies and user experiments

G. De Ninno

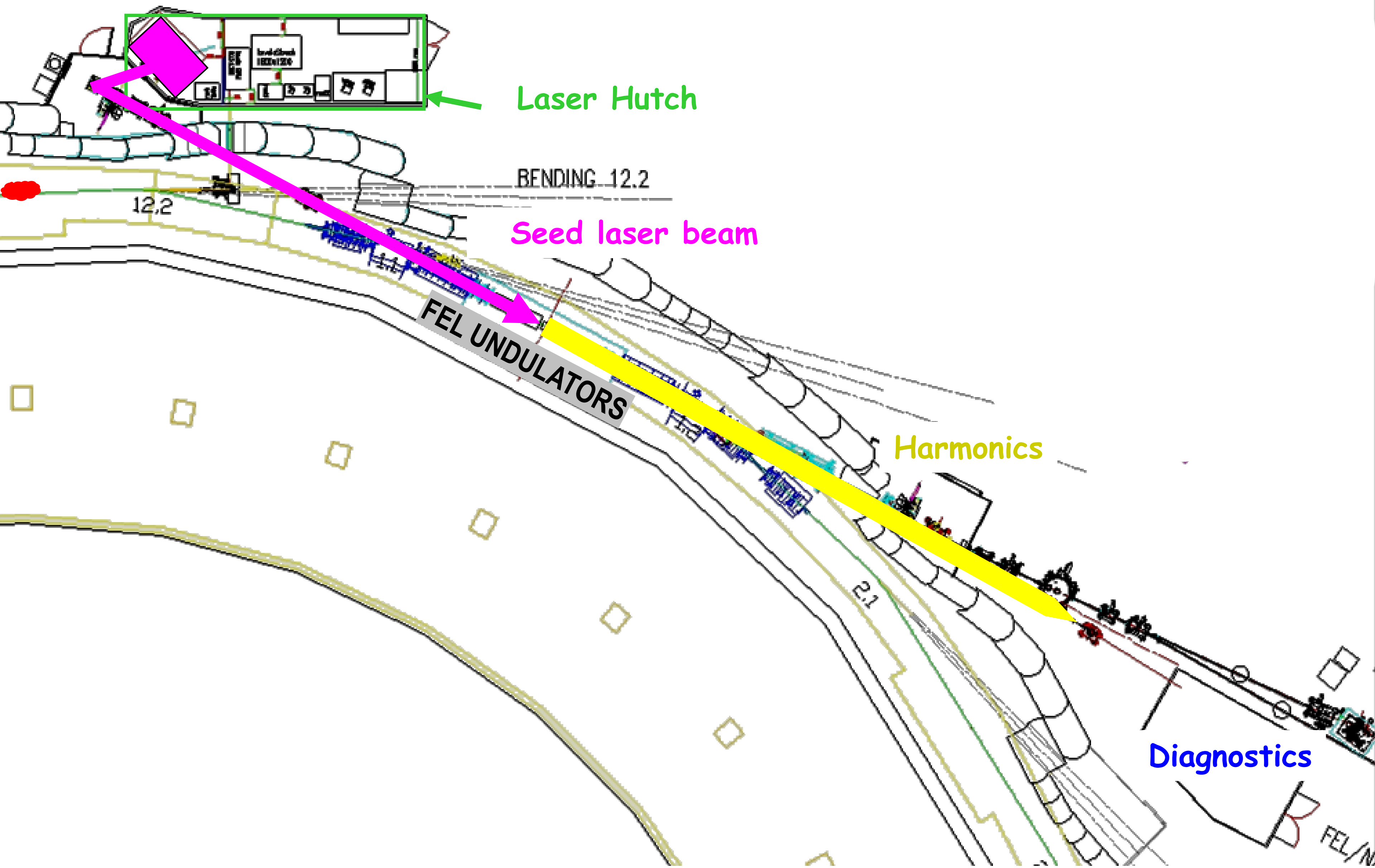
(University of Nova Gorica and Sincrotrone Trieste)

Experiment layout

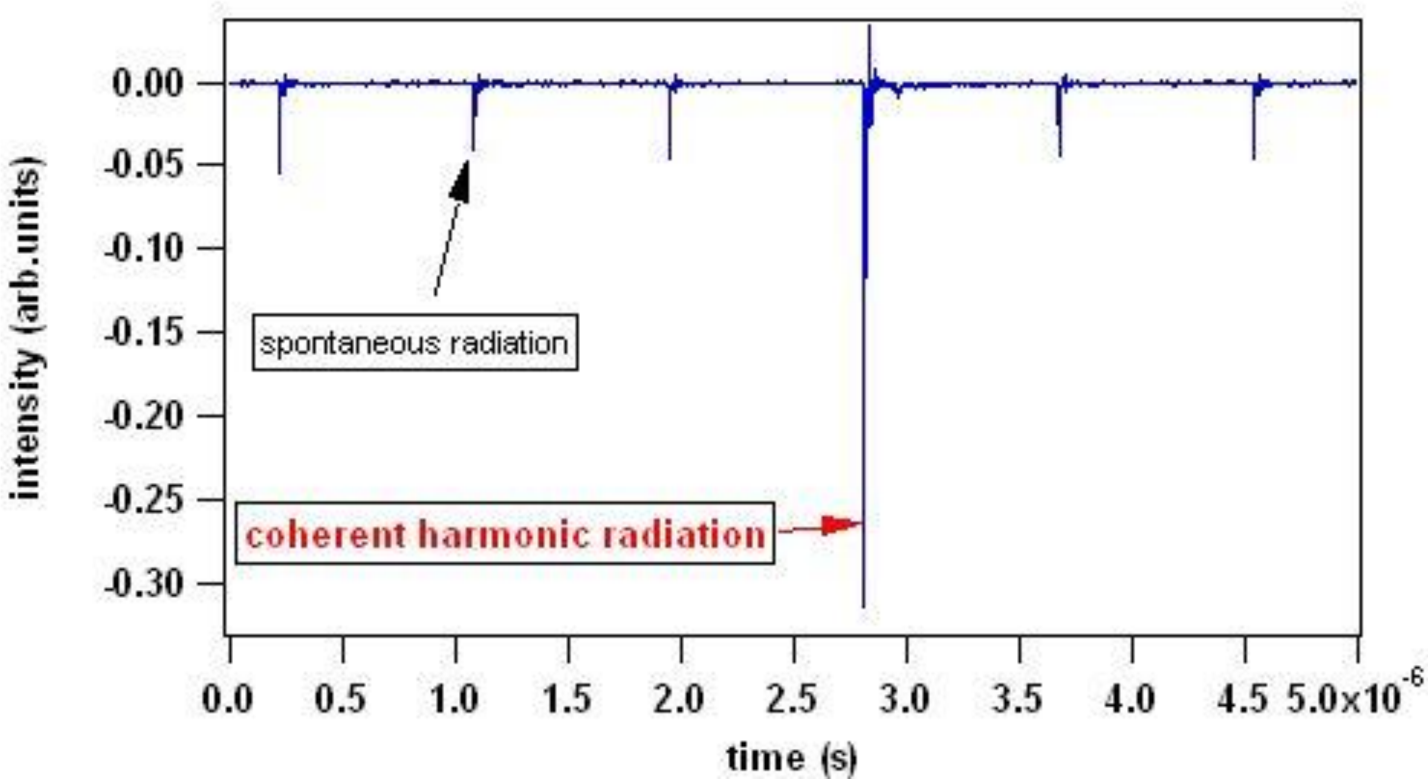


Elettra working conditions	
Beam energy	0.75 GeV Ğ1 GeV
Current per (single) bunch (max)	~ 1 mA
Normalized H/V emittance (1GeV)	3.2/0.32 mm mrad
Bunch duration	~ 30 ps (FWHM)
Bunch relative energy spread	~ 10^{-3}

FEL working principle



Harmonic generation: temporal analysis

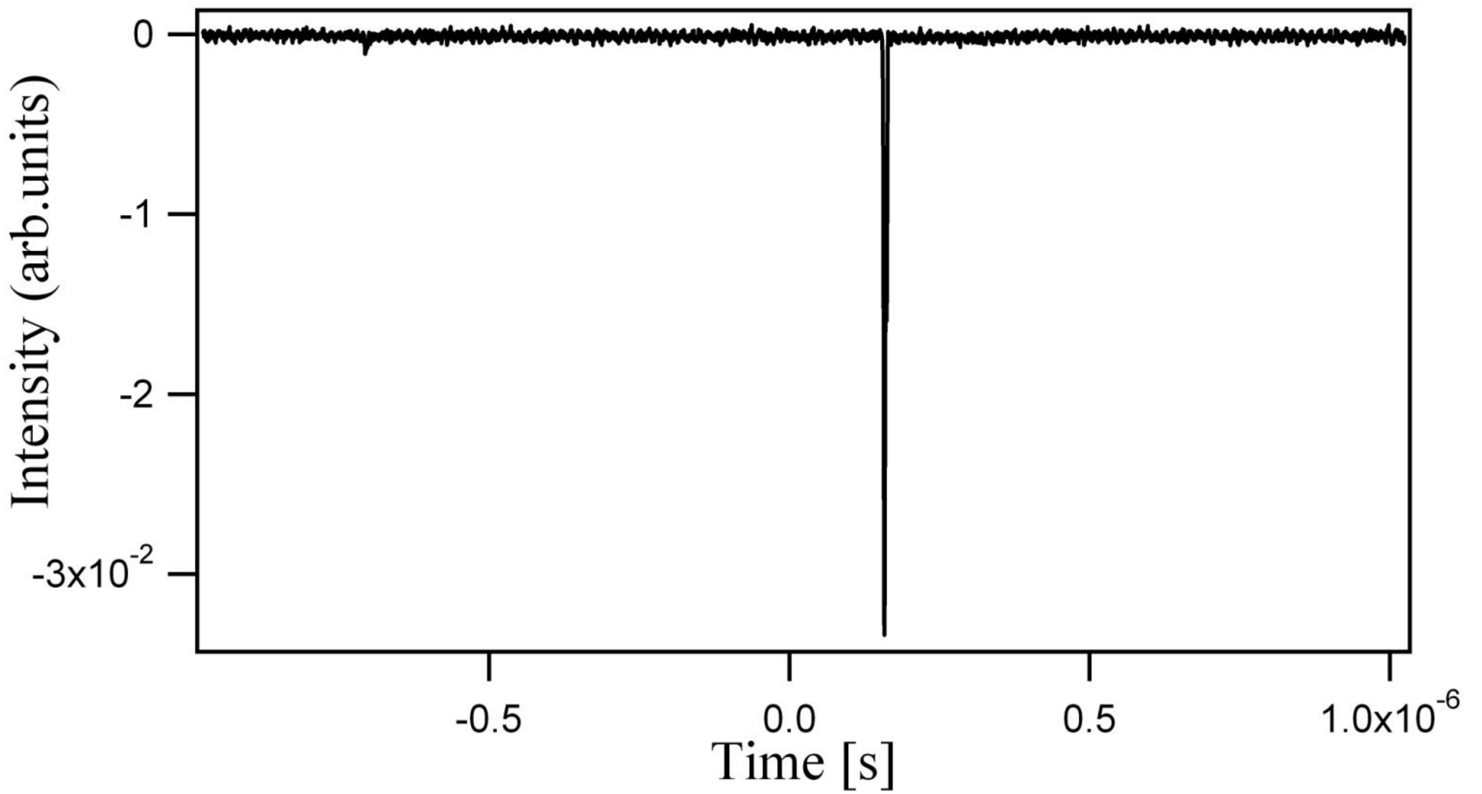


Vertical axis: integrated signal of the monochromatized radiation at 260 nm acquired with a photo-multiplier tube. Horizontal axis: acquisition time. The enhanced peak is the coherent signal generated by the seeded electron bunch, small peaks represent the spontaneous (i.e., un-seeded) radiation.

Pulse repetition rate: 1 KHz; pulse length: 100 fs (FWHM)

After some tuning…

synchrotron radiation falls into noise!

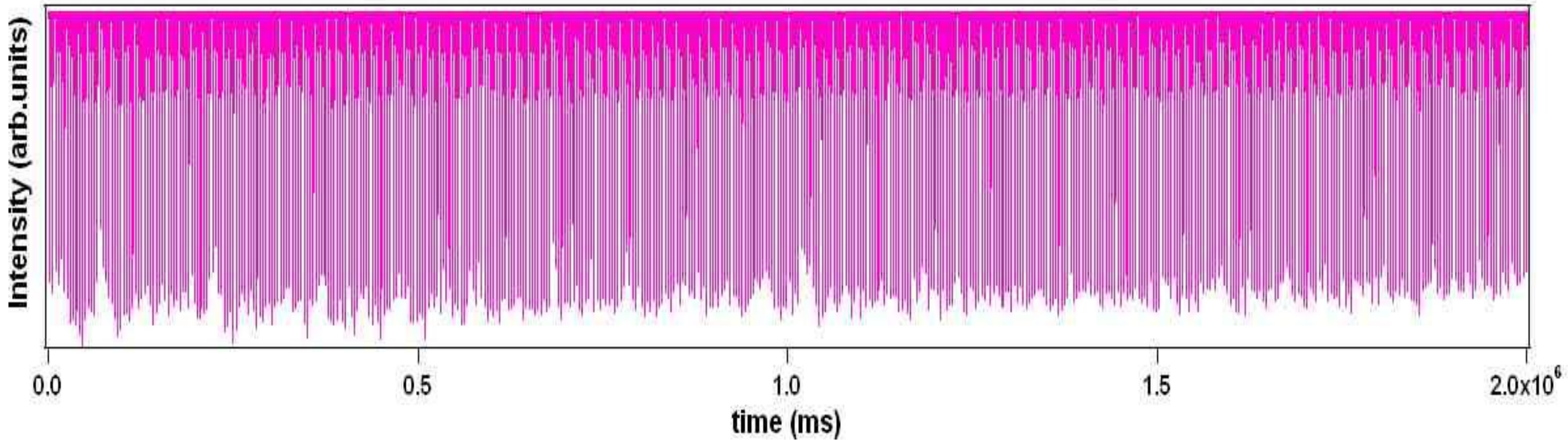


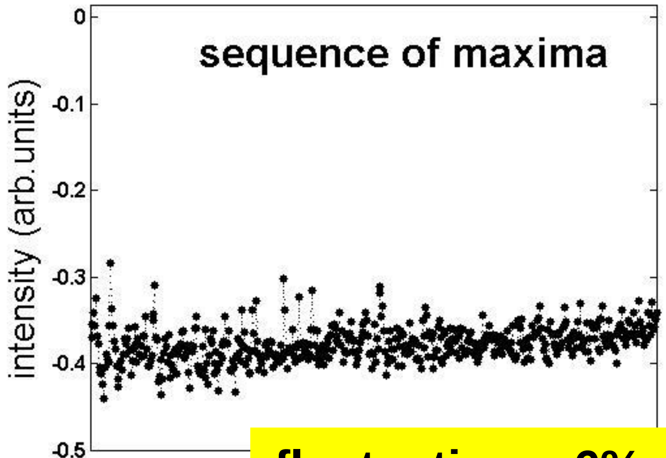
Seeded signal is a factor about **50** above spontaneous emission.

The factor becomes about **10^4** taking into account the difference between spontaneous (30 ps) and seed (100 fs) pulse durations.

Shot-to-shot stability

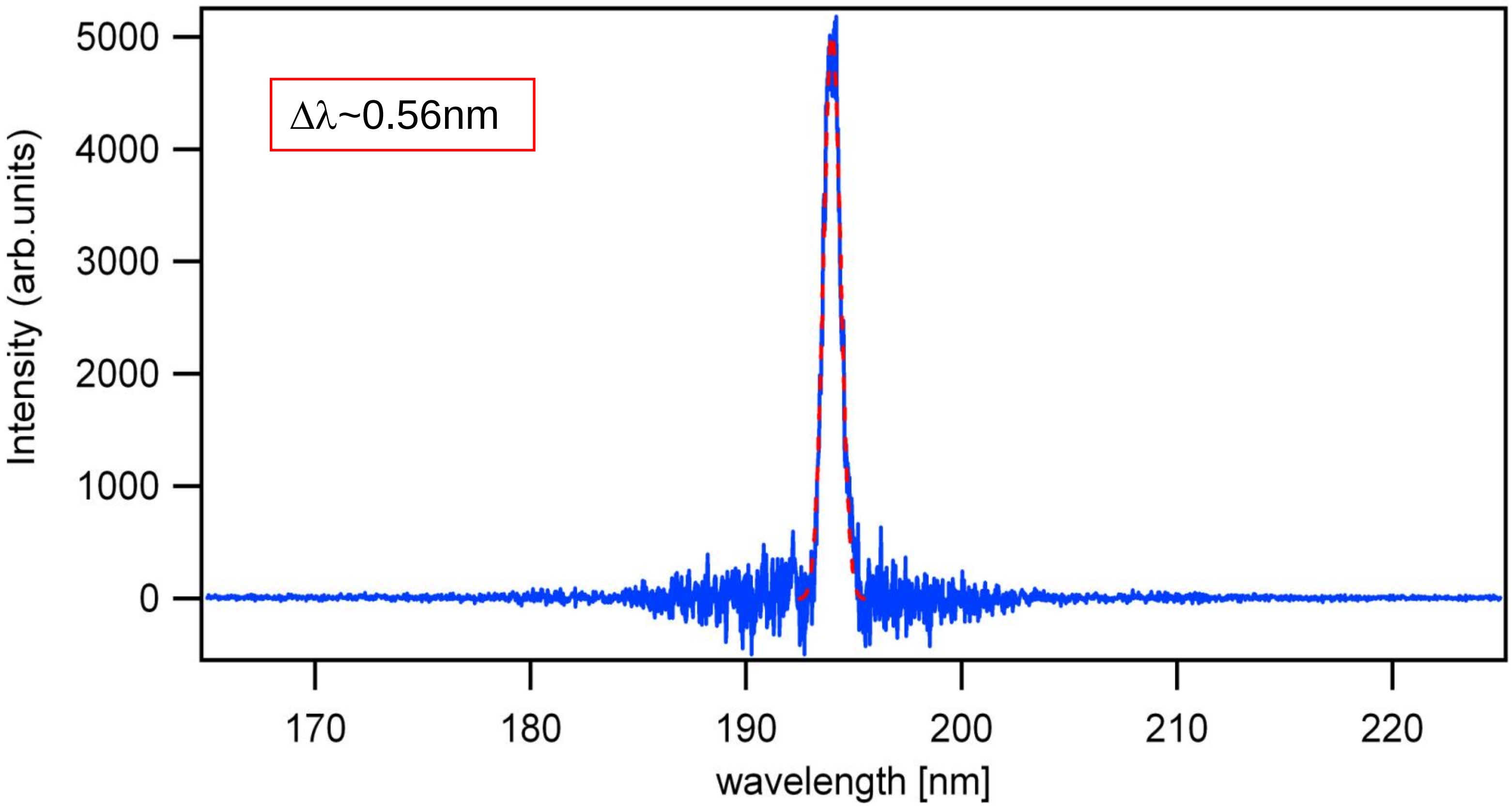
Sequence of 500 coherent pulses





fluctuation ~ 6%

Harmonic generation: spectrum



Optical pulse is close to Fourier limit

Recent activities

- FEL physics:

Tunability of a seeded free-electron laser through frequency pulling

Spectral distribution and polarization of FEL harmonic emission

- Source developments:

CHG signal at 87 nm

FEL radiation at 1.5 GeV of electron energy

Installation of an optical setup for pump-probe experiments

-Test user experiments:

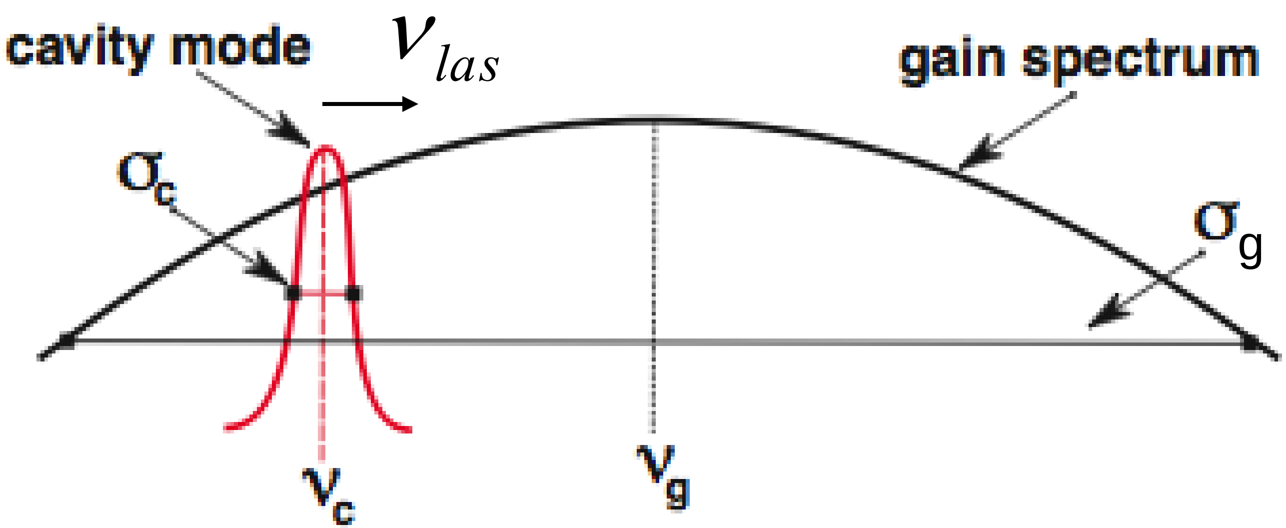
Time-resolved two-photon ionization on Acetylene

Time-resolved diffraction from self-organized stripe domains in MnAs/GaAs (001)

FEL physics

Frequency pulling in standard lasers

In standard lasers, frequency pulling takes place when the peak of the gain spectrum is slightly detuned with respect to the frequency of one of the modes selected by the laser cavity.



When this occurs, the lasing frequency is close to the one of the selected mode, but slightly "pulled" towards the maximum of the gain curve:

$$\nu_{las} = \nu_c - \left(\nu_c - \nu_g\right)\frac{\sigma_c}{\sigma_c + \sigma_g}$$

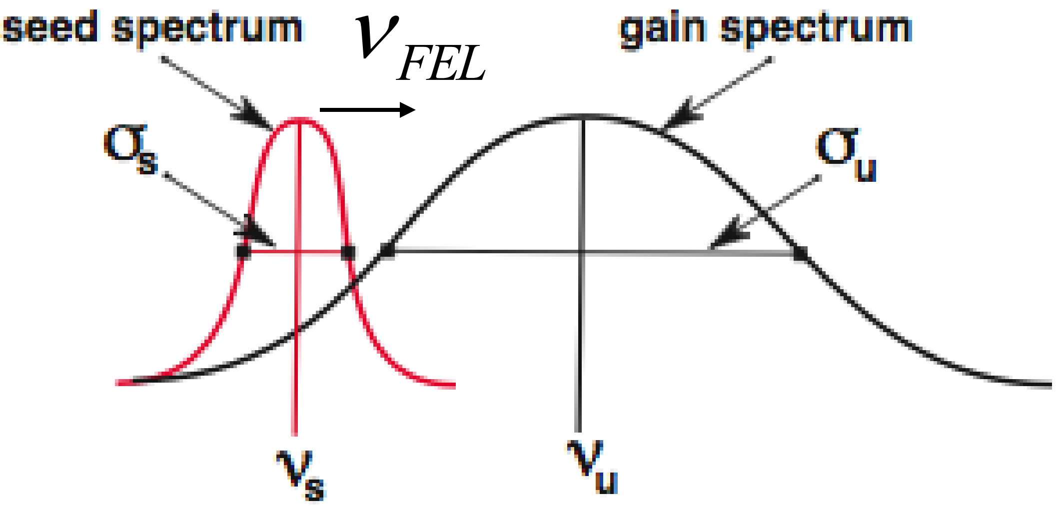
Frequency pulling in FEL's

Is there a similar phenomenon in a seeded single-pass FEL's?

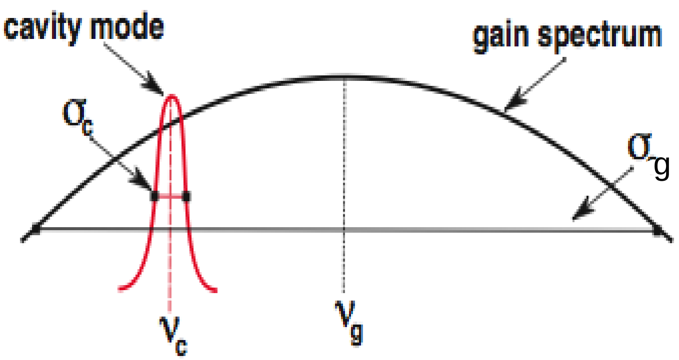
If yes, is it possible to exploit it to tune the frequency of a seeded FEL around the frequency imposed by the seed?

What is the relation determining the FEL frequency in the presence of frequency pulling?

seeded FEL

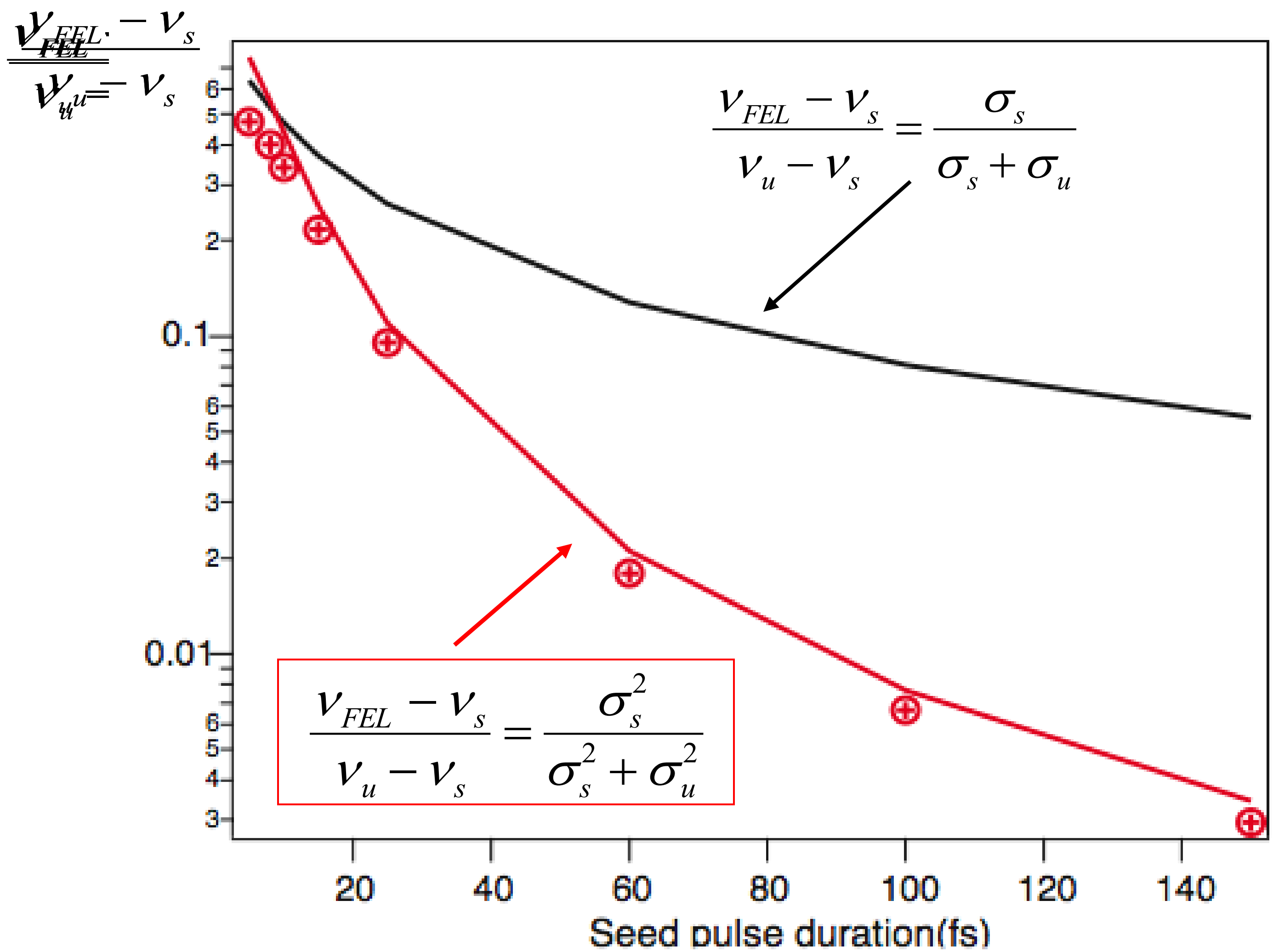


standard laser



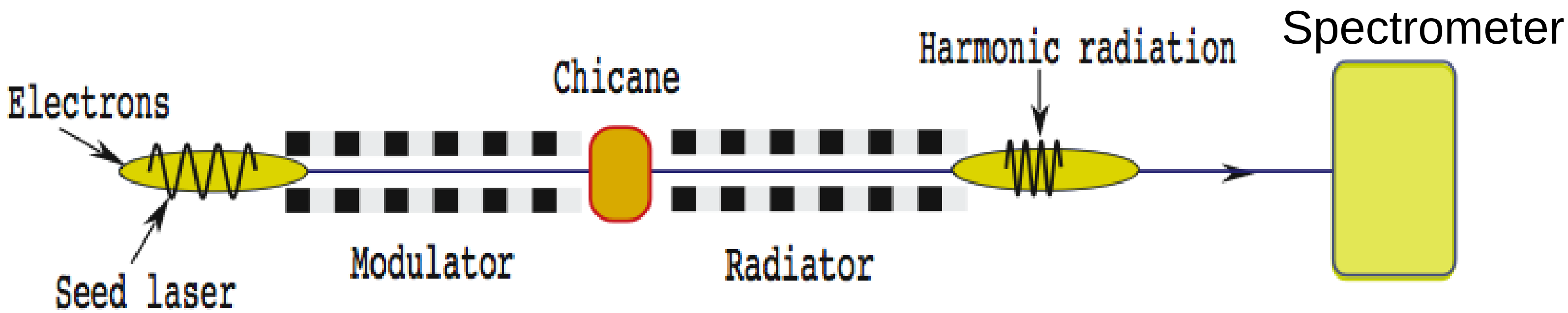
Frequency pulling in FEL's:
Numerical demonstration

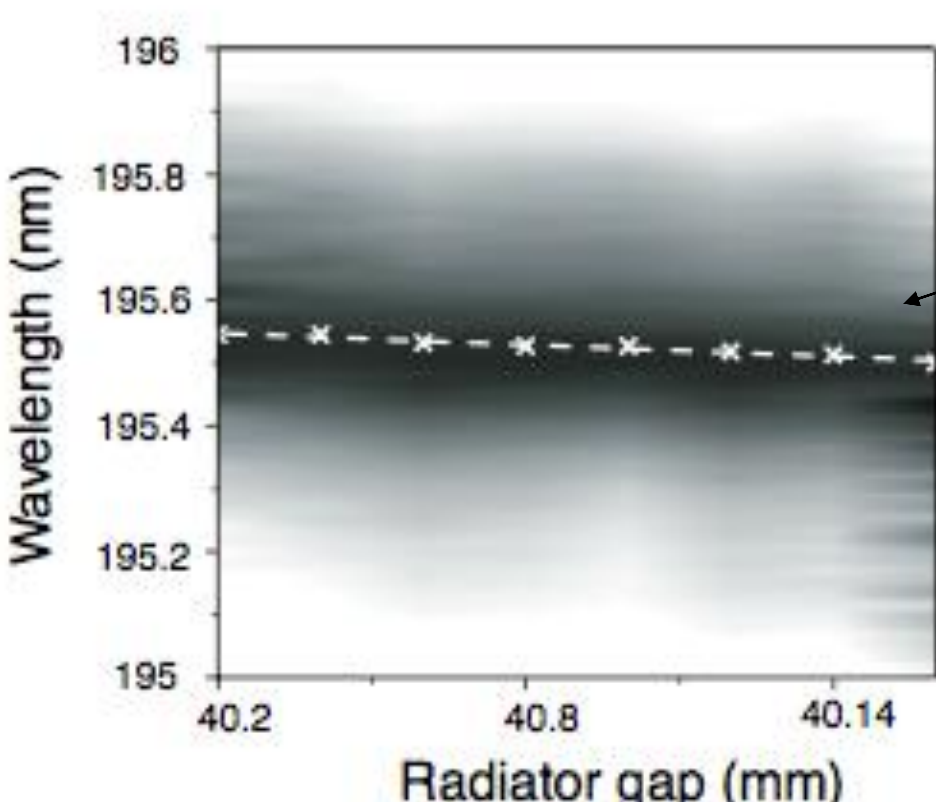
Simulations using GINGER



E. Allaria, G. De Ninno, M.B. Danailov
EPL ***89*** *64005 (2010)*

Frequency pulling in FEL's:
Experimental demonstration





$$\frac{\nu_{FEL} - \nu_s}{\nu_u - \nu_s} = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_u^2}$$

E. Allaria, C. Spezzani, G. De Ninno,
Submitted to PRL

Nonlinear harmonic generation in helical undulators

Variable polarization is one of the most attractive features of FEL's relying on APPLE-type undulators. On the other hand, <u>it is well known that harmonic (spontaneous and FEL) radiation generated by helical undulators is distributed off axis</u>. In principle, this prevents the possibility to generate significant FEL flux at high harmonics, while maintaining polarization ductility.

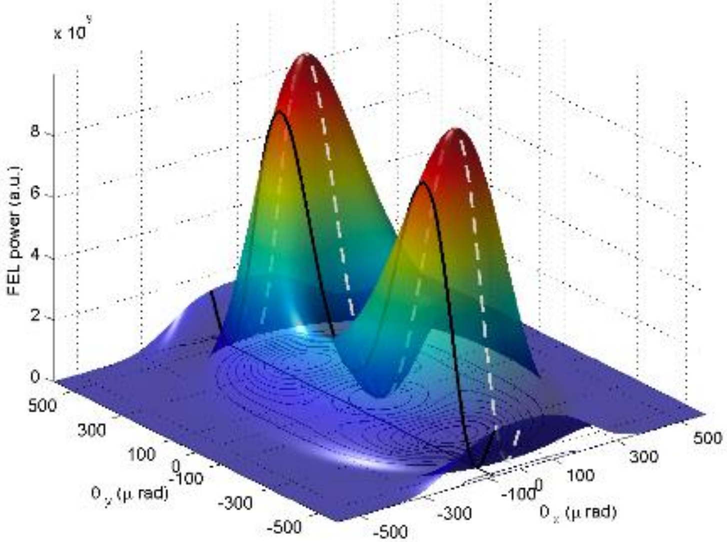
The studies we carried out aimed at answering the following questions:

1) Is it possible to recover "significant" harmonic flux by collecting the out-of-axis radiation generated by a helical undulator?

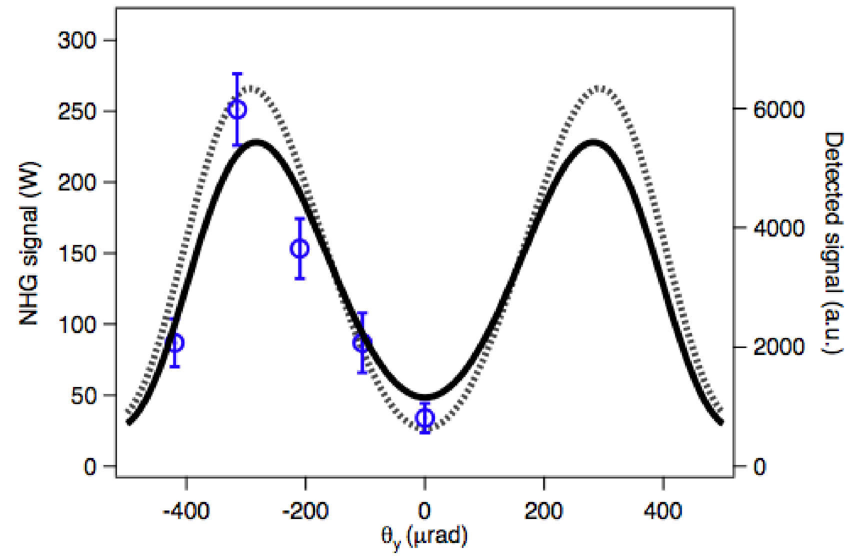
2) Is there a way to recover polarization ductility, e.g. by playing with the undulator phase?

Angular distribution of FEL harmonic radiation

Theory



Experiment



We performed a complete characterization of the angular distribution of the FEL harmonic radiation generated by a helical undulator. Experiments are in good agreement with the theory developed by *Geloni et al*..

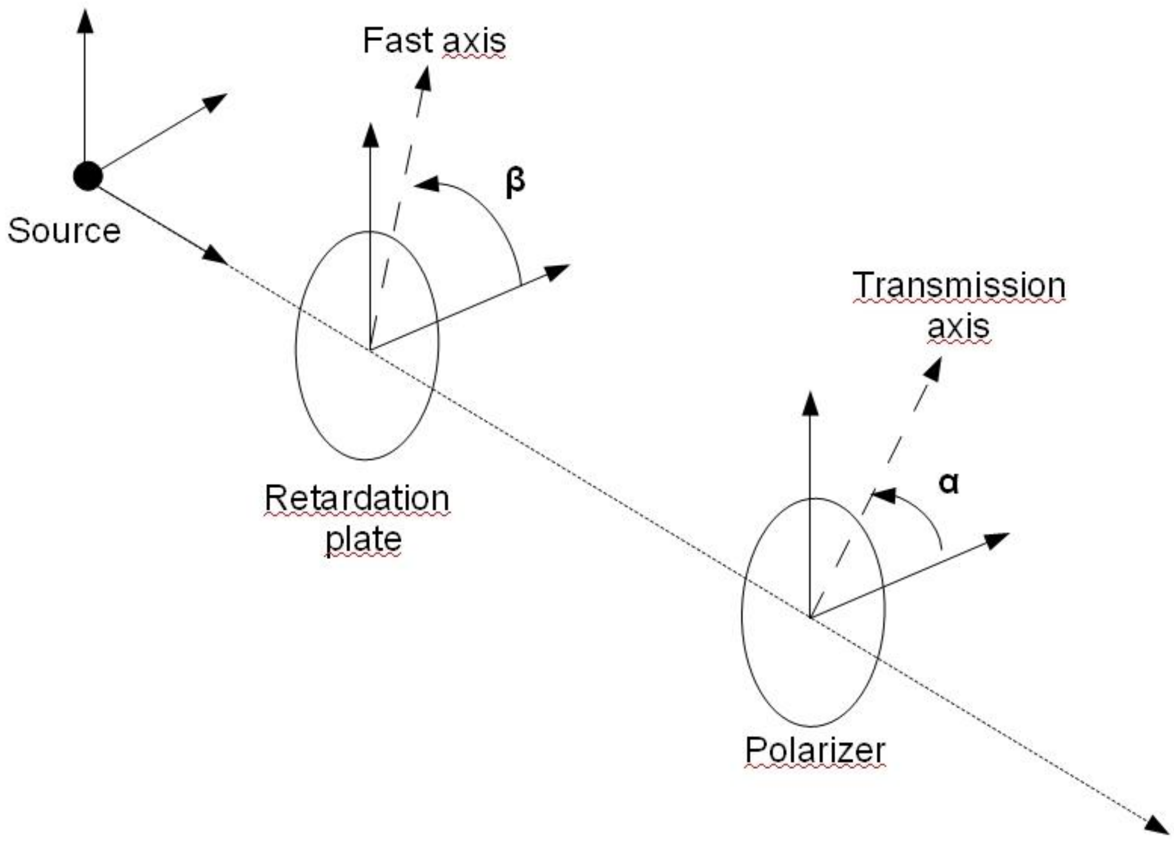
According to our results, collecting off-axis emission does not allow to recover significant harmonic flux. In the FERMI@Elettra case, one can predict ~$3 \cdot 10^{12}$ ph/pulse at 5 nm, ~10^8 on the second harmonic and ~10^4 on the third harmonic (W. Fawley, provate communication).

E. Allaria, G. De Ninno, G. Geloni, C. Spezzani, submitted to Phys. Rev. Spec. Topics

Degree of polarization of FEL harmonic light

Experimental setup

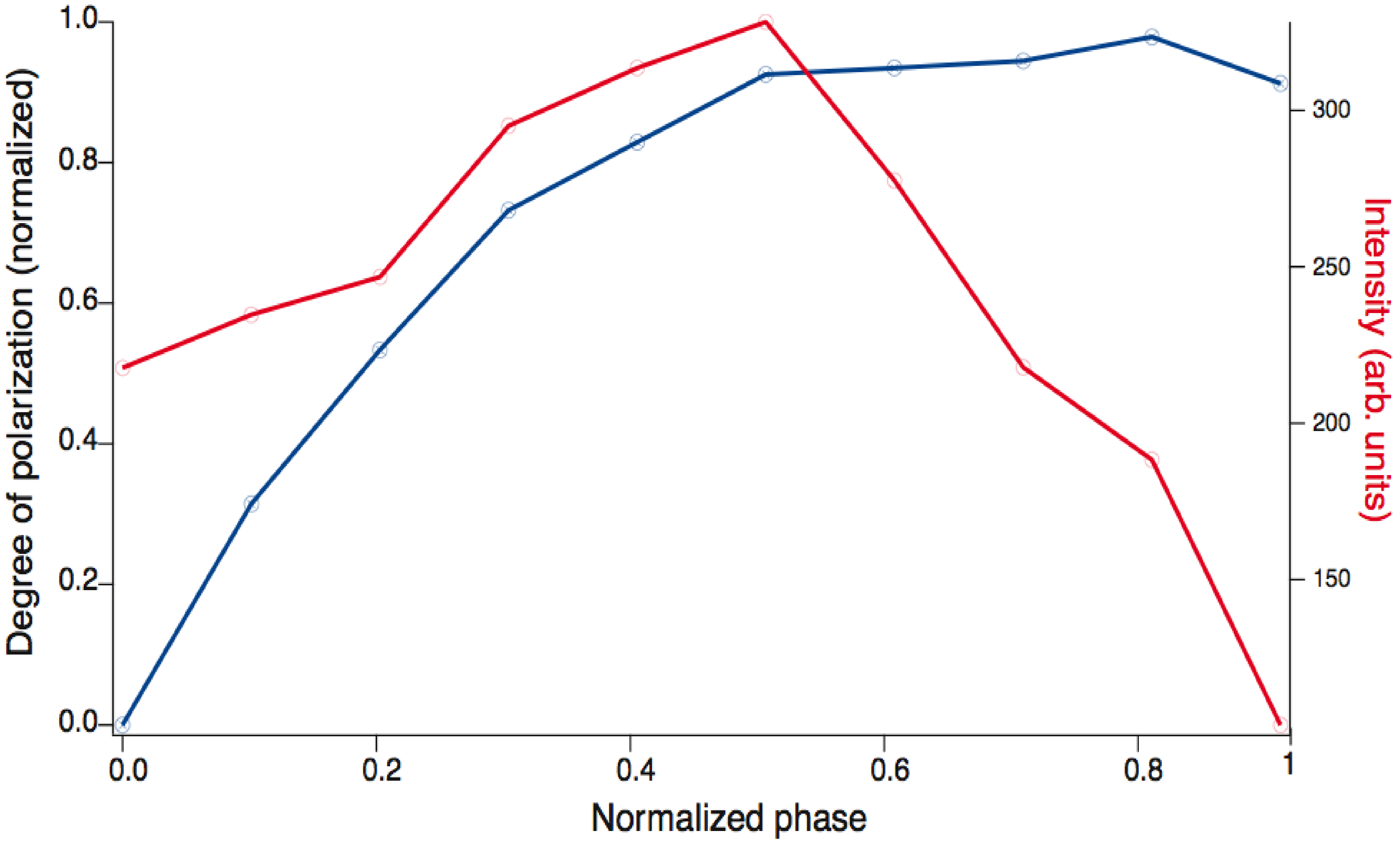
[from H.G. Berry et al., Appl. Opt. 16, 12, 3200 (1977)]



Modulator tuned at 390 nm, radiator tuned at 585 nm

Observed wavelength: 195 nm (third harmonic of radiator fundamental wavelength)

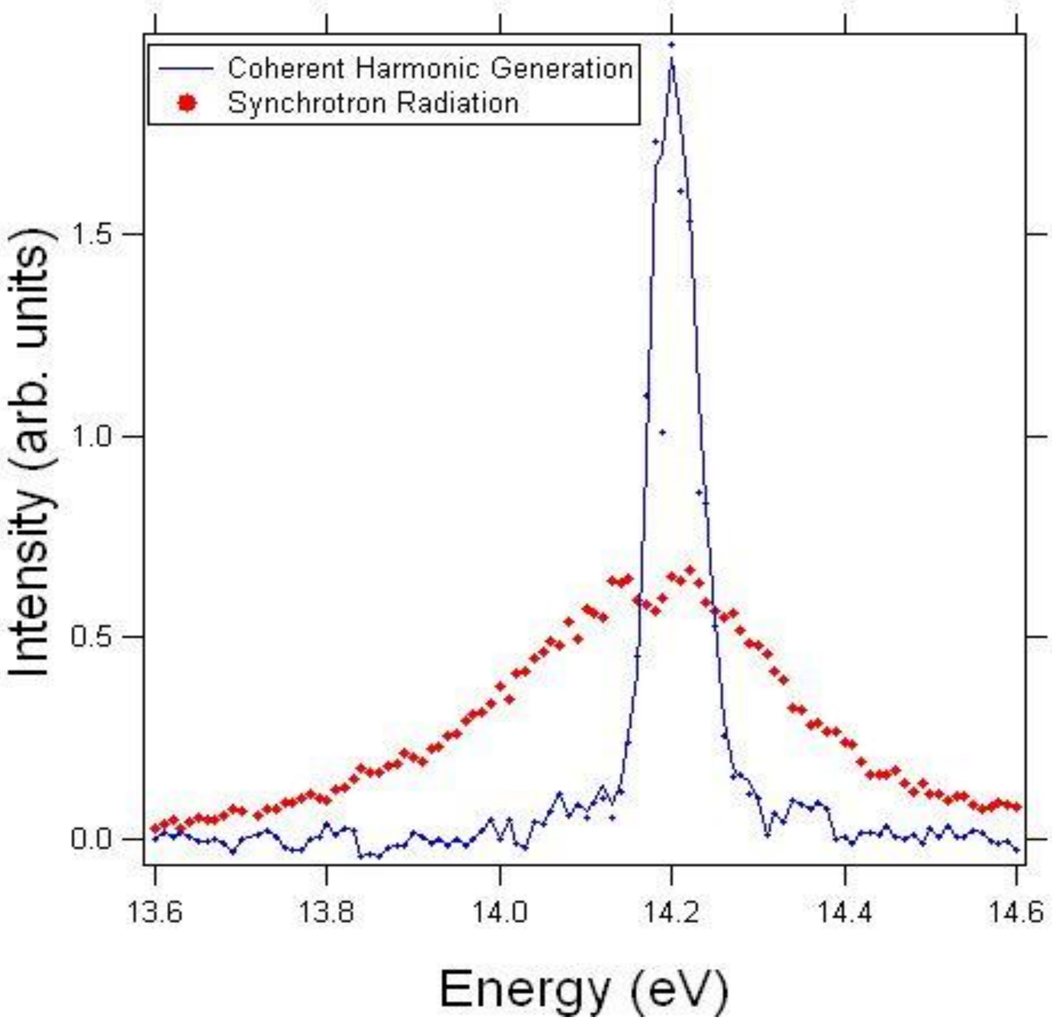
On-axis circular polarization of FEL third harmonic vs. radiator phase



Source developments

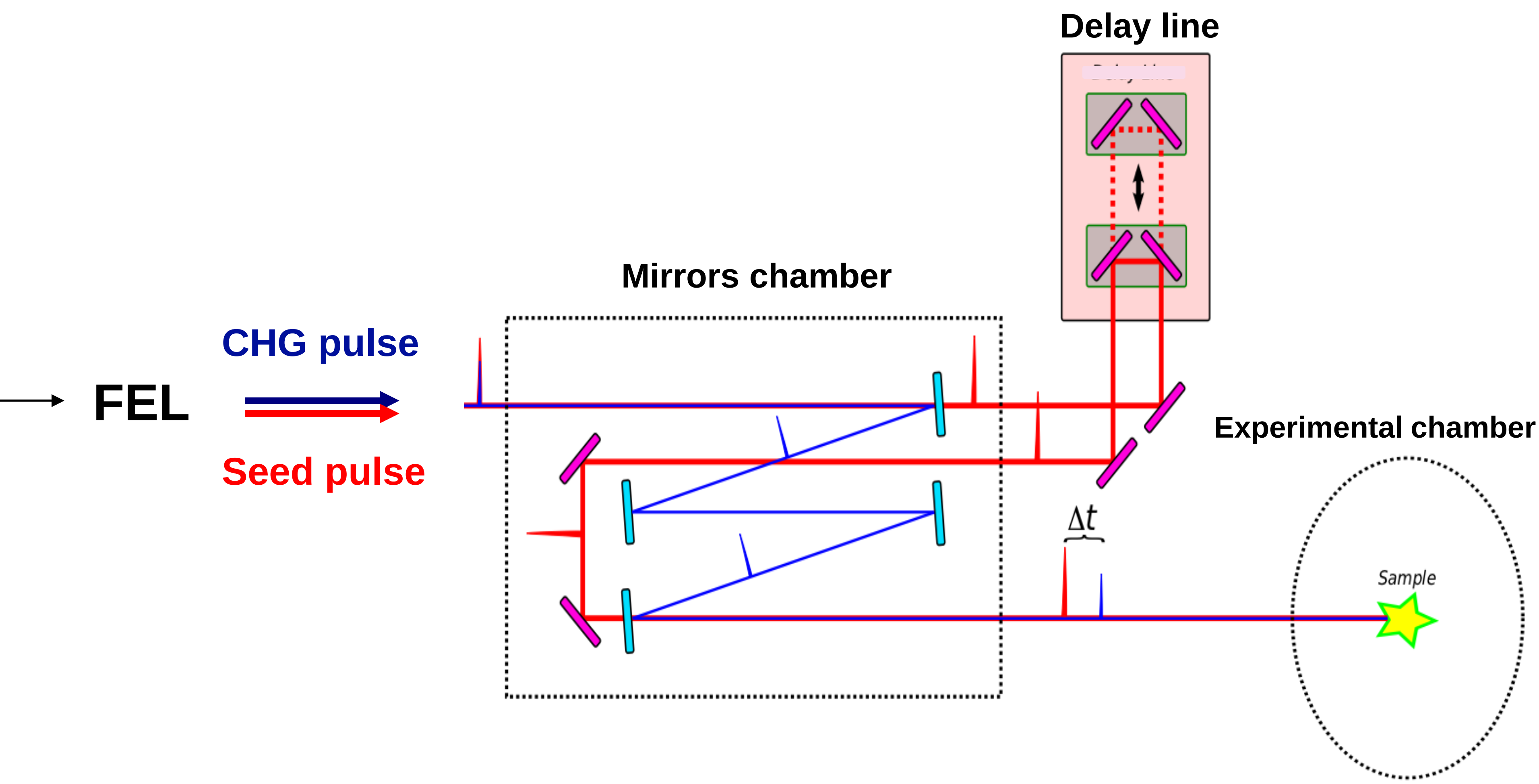
Coherent harmonic generation at 87 nm

The SPELEEM microscope installed at the Elettra Nanospectroscopy beamline was used to observe the photo-electron yield from a **Au** thin film, as function of the photon energy



11/05/2009

Set-up for pump-probe experiments



Delay line:
Resolution: 100 fs
Scanning range: 0-2 ps

Test user experiments

Time-resolved two-photon ionization on Acetylene

TOF e^- and ion spectroscopy

Principal investigators:

M. Coreno (CNR-IMIP)

C. Spezzani (Elettra)

In collaboration with:

M. Stankiewicz

(Jagiellonian University,

Krakow, Poland)

Motivations: Demonstrate feasibility of pump-probe experiments in gas phase with sub-ps temporal resolution

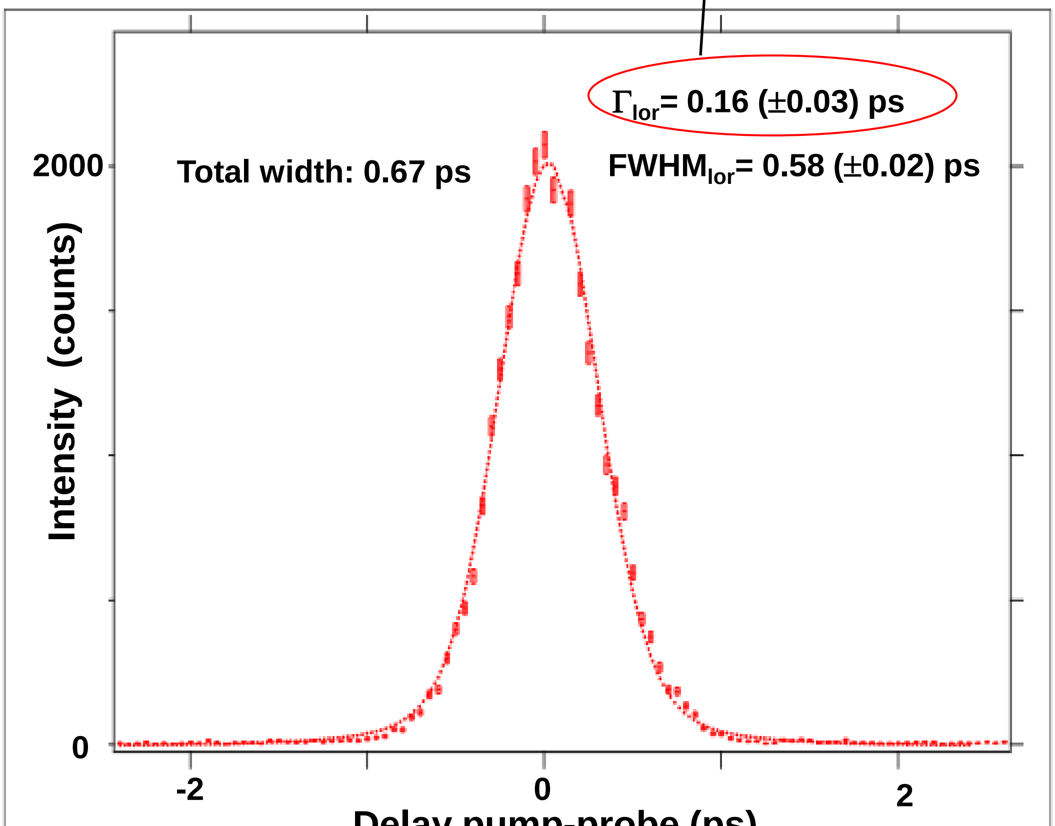
Time-resolved two-photon ionization on Acetylene

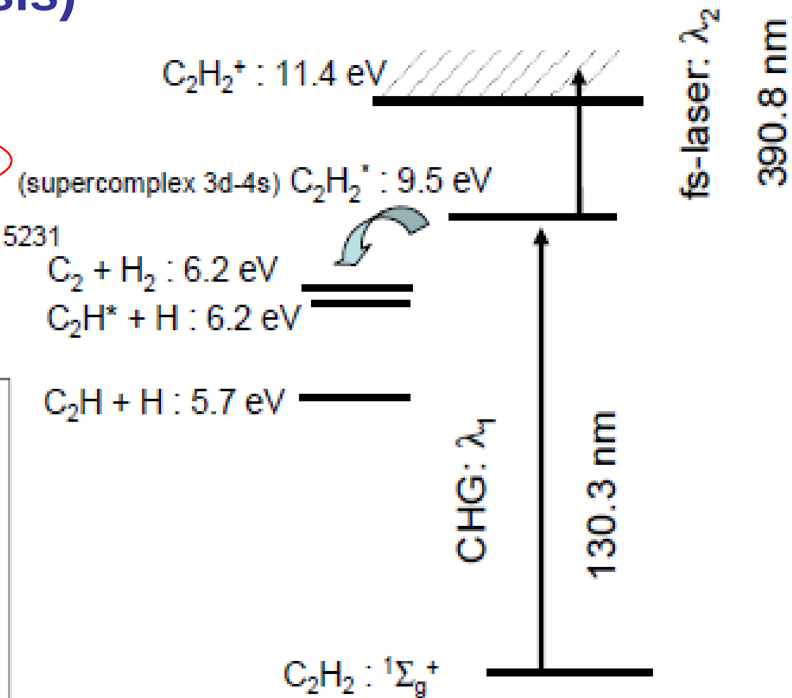
(data analysis)

Pump: CHG at 130.3 nm

Probe: seed laser at 390.8 nm

lifetime τ ~ 150 fs
P. Loeffler et al,
JChemPhys 108 (1998) 5231





<u>Good agreement</u>
<u>with already published results</u>

but…

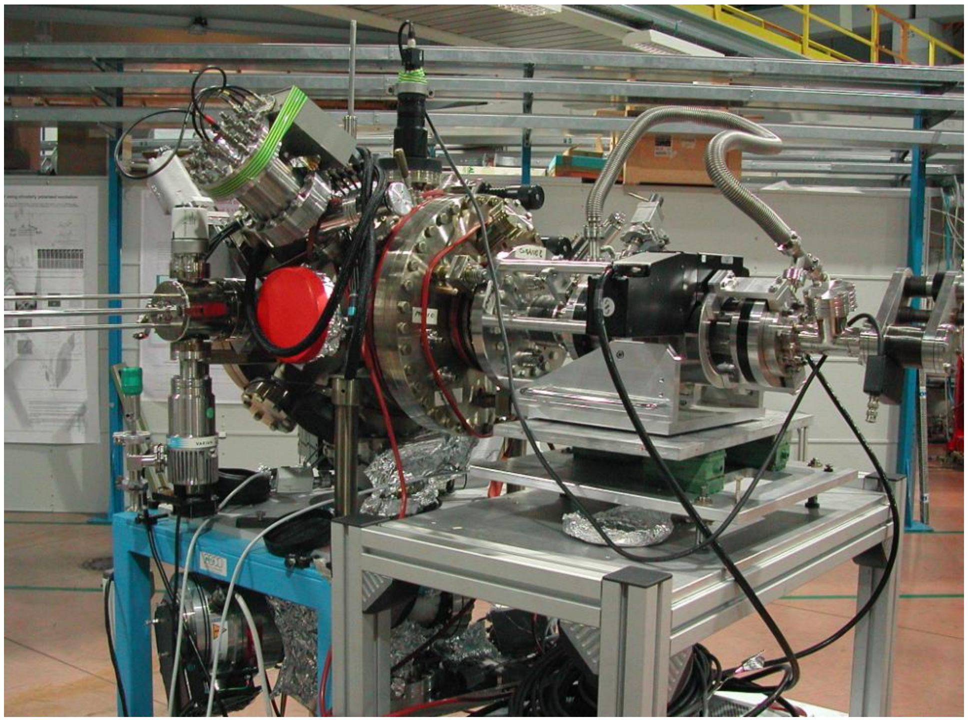
large instrumental width
(to be improved)

Time-resolved diffraction from self-organized stripe domains in MnAs/GaAs (001)

(set-up and motivation)

IRMA reflectometer

M. Sacchi et al., Rev. Sci. Instrum. 74, 2791 (2003)



Principal investigators:

M. Sacchi (CNRS, SOLEIL)

C. Spezzani (Elettra)

Motivations: “Local” induction and dynamical characterization of coexistence between ferromagnetic (α) and non-magnetic (β) phases in a MnAs/GaAs (001) sample. The sample can serve as magnetically active template for temperature driven magnetization reversal of a ferromagnetic overlayer

MnAs/GaAs(001): a temperature controlled magnetically active template

0 °C 20 °C 35 °C 50 °C

M. Sacchi et al., Phys. Rev. B 77, 165317 (2008)

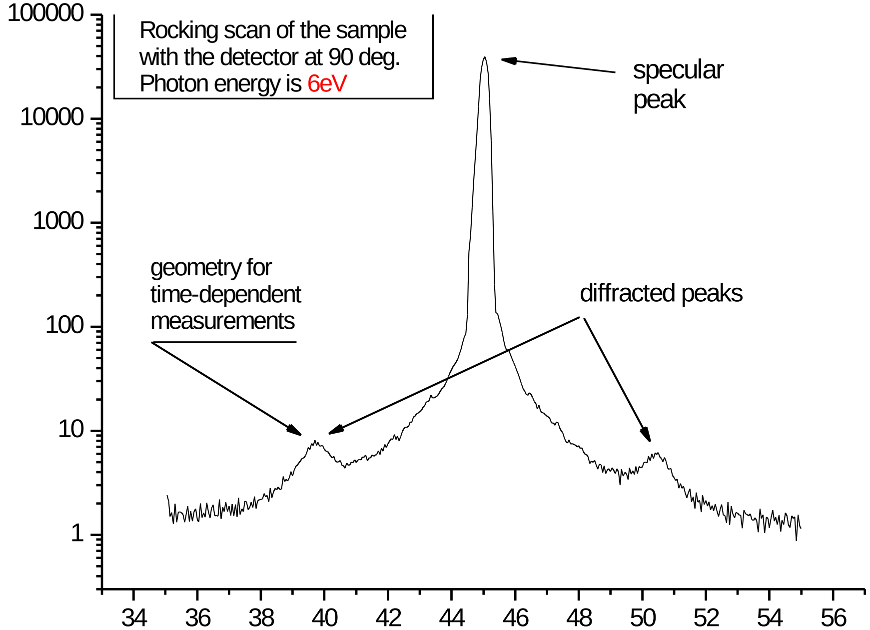
- Coexistence of **α** (**ferromagnetic**) and **β** (**paramagnetic**) phases over the temperature range 10-40 ° C

- The MnAs layer thickness **t** controls the period **p** of the stripes (**p ≈ 5 t**) and the height **d** of the steps (**d ≈ 0.01 t**). Typically, **t**=50-200 nm.

- The width of α and β stripes within a period varies continuously with temperature

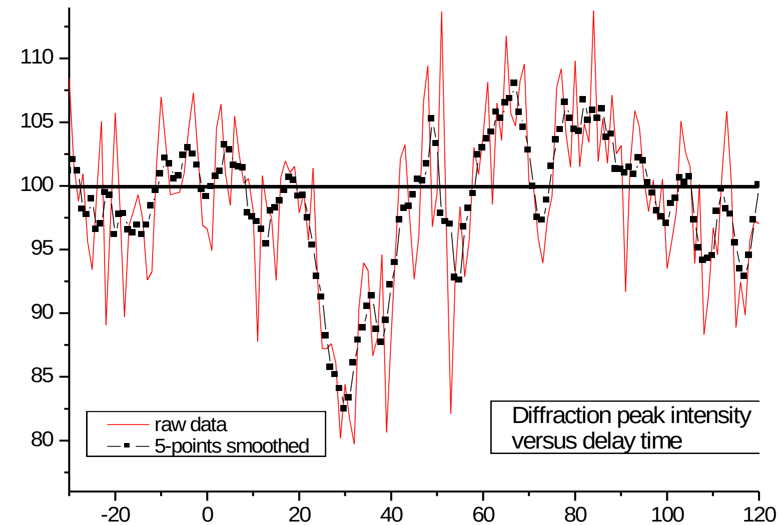
Aim of the experiment: induce local magnetization switching by focusing the seed laser (at 400 nm) onto the sample and use the CHG (at 200 nm) light to investigate the dynamics of the appearance and disappearance of the stripes in the phase coexistence region

Preliminary results



We observed the stripe-related diffraction peaks with 200nm radiation

Detector at 90 deg. Sample at 39.7 deg.
Sample temperature: 29 deg.



We set up a pump-probe experiment with 100 fs time resolution; we observed a time dependence of the diffracted intensity after a laser pulse, with a sharp decrease and a recovery to the initial value, taking place over a 20 ps interval.

Elettra Storage-Ring FEL:
Present performance

Spectral range

Seed (nm)	CHG (nm)	
λ	λ/2	λ/3
780	390	260
390	195	130
260	**130**	**87**

- photons/pulse: $10^9 \div 10^{10}$ (at 130 nm)
- ***pulse length: ~100 fs (FWHM)***
- repetition rate: 1 kHz
- ***polarization: fully variable***
- good longitudinal and transverse coherence
- ***good spectral and power shot-to-shot stability***

Perspectives for source developments

- Obtain compatibility with standard user mode (**first priority!)**

This will drastically increase the possibility to get more beam time, providing the chance to prepare and successfully carry out some user experiments.

Recently, **we obtained CHG at 1.5 GeV**. To obtain compatibility we should reach 2/2.4 GeV (two issues: energy spread, get resonance in the modulator at 2 GeV), and to work in multibunch.

-Extend accessible spectral range towards shorter wavelengths, improve tunability

Need to significantly increase the available seed power

-Explore (both theoretically and experimentally) the possibility to use the FEL setup to perform femto-slicing and to generate THz radiation, possibly to be exploited for user experiments.

Need to better understand (and possibly play with) Elettra's electron-beam dynamics

Perspectives for users experiments

Gas phase:

spectroscopy and dynamics of excited states *(femtochemistry, exotic species)*

Next steps for pump-probe experiments with ion and elector TOF techniques: repeat two photon ionization experiment on acetylene, then H_2O and Xe.

Towards a cross correlation with two photon ionization on gases:

- H_20, low cross section for excited states at 130 nm ($\Gamma \sim 50$ fs)
- Xe is only close to resonance (Xe $5p_{1/2}$-6s @129.3 nm): proper cross correlation

Solid state:

Continue the experiment on MnAs/GaAs(001), with the following main goals:

1) Determine the time scale governing the formation and disappearance of the magnetic stripes and, in turn, 2) of the magnetization reversal of a ferromagnetic overlayer

SR-FEL Group

G. De Ninno, E. Allaria, M. Coreno, E. Ferrari, L. Romanzin, C. Spezzani, M. Trovò

Machine

E. Karantzoulis + Linac and Elettra operators

Laser

M. B. Danailov, A. Demidovich, R. K. Ivanov, P. Nikolov Ivaylo

Synchronization

P. Sigalotti, A. Winter, A. Carniel, F. Rossi, M. Ferianis

Experiments

M. Sacchi, M. Stankiewicz, A. Locatelli, O. Mentes, M.A. Nino, R. Sergo, M. Pittana, G. Cautero

+

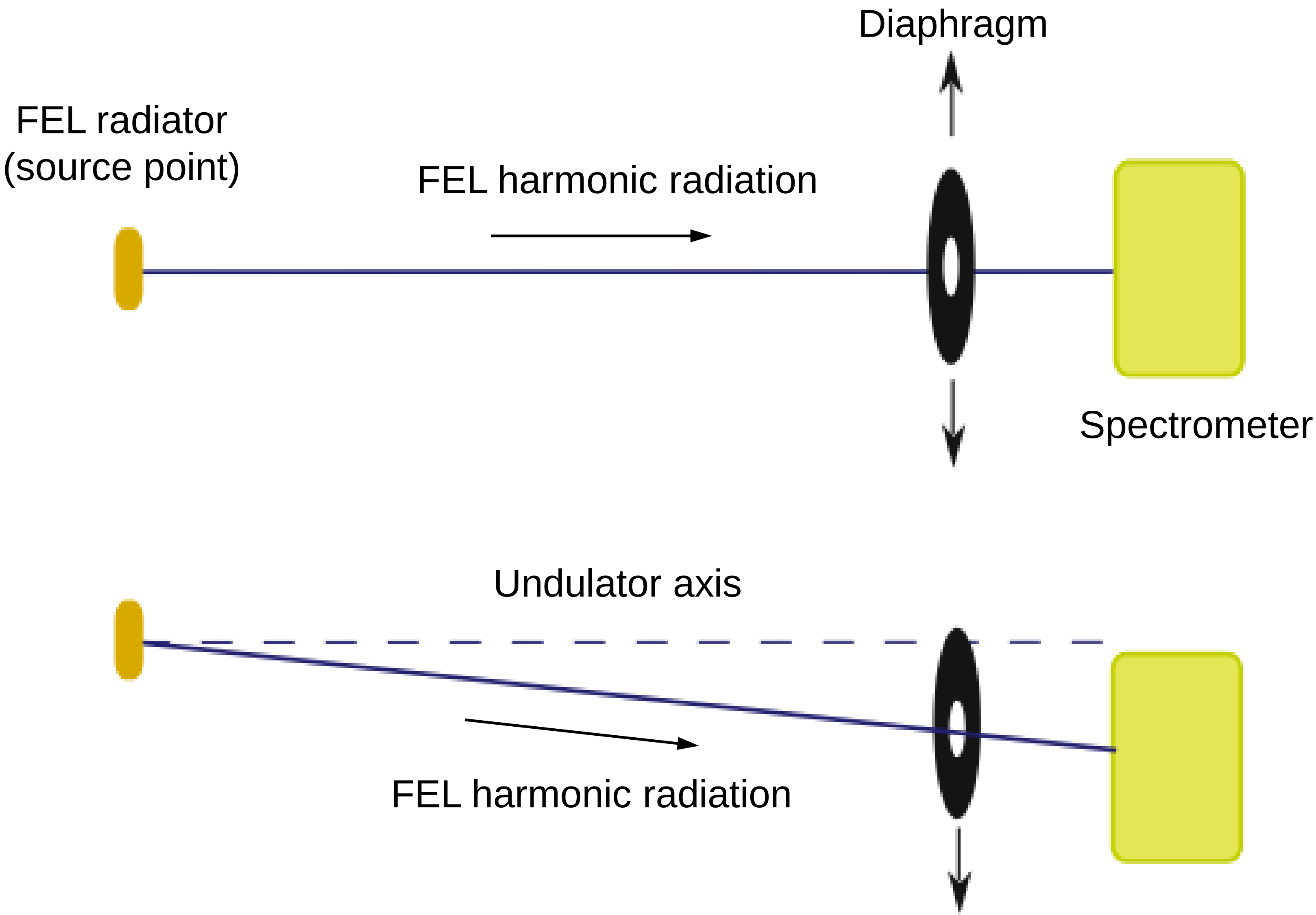
J. Urbancic (Master student at Nova Gorica University),

B. Mahieu (PhD student at Nova Gorica University)

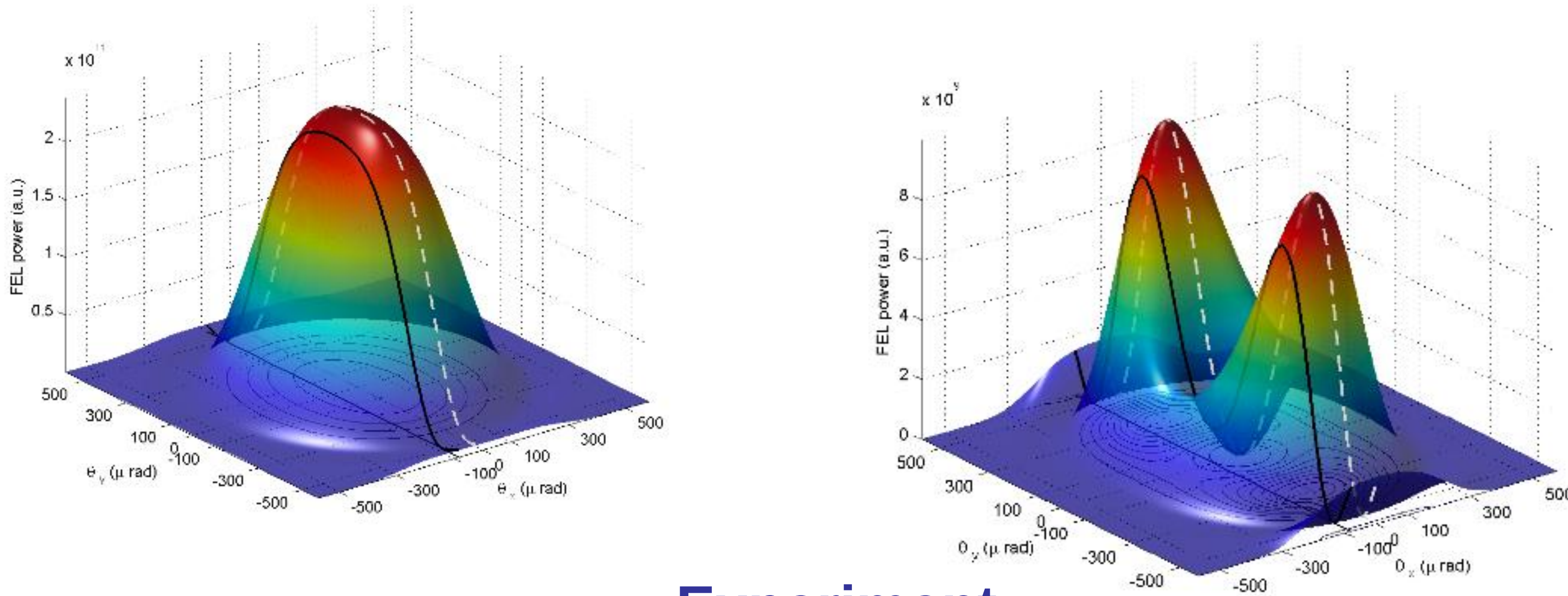
F. Curbis (presently at Desy)

Angular distribution

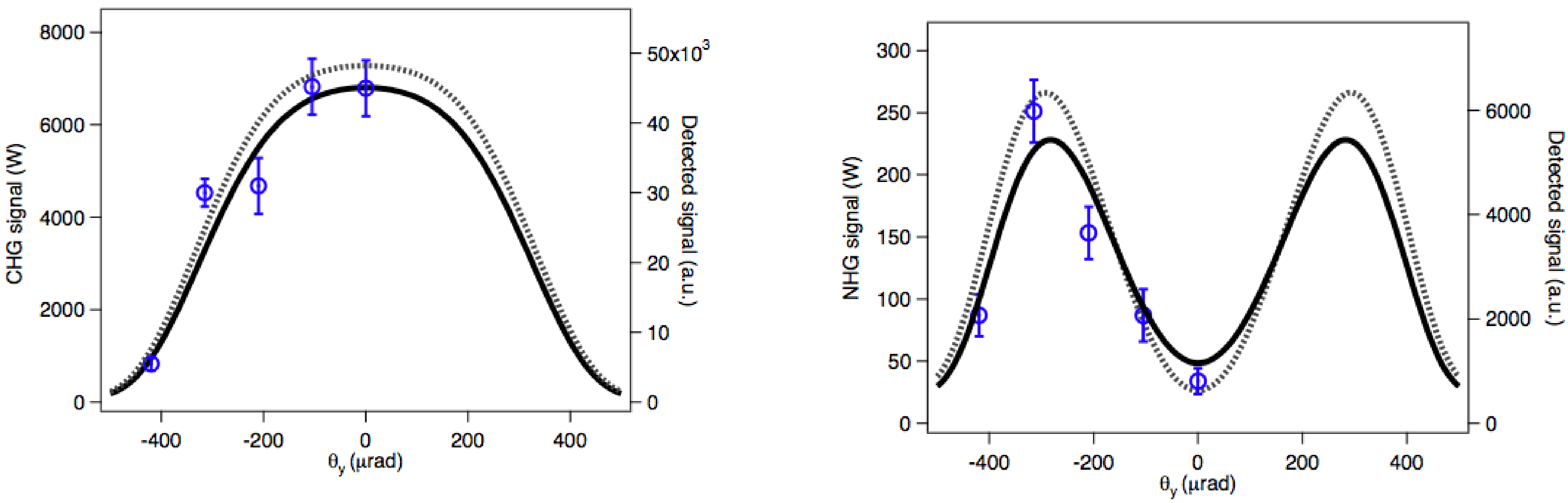
Layout



Theory

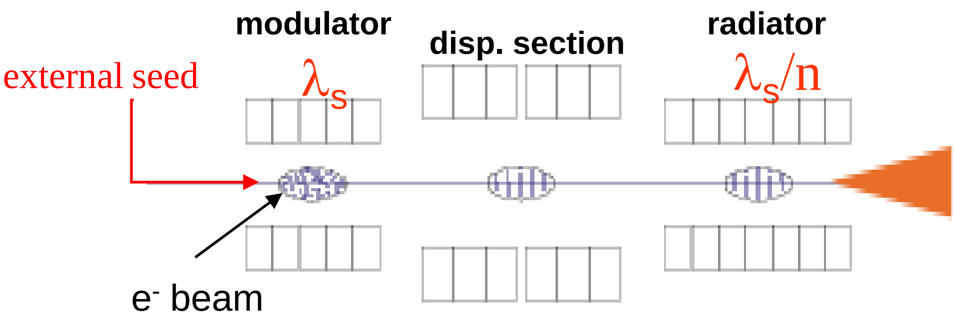


Experiment

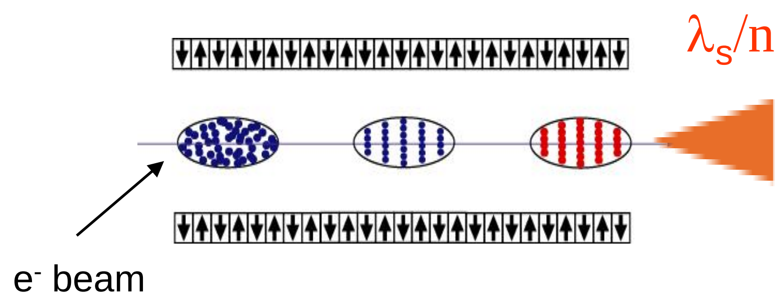


Characterization of out-of-axis harmonic emission
(FEL configurations)

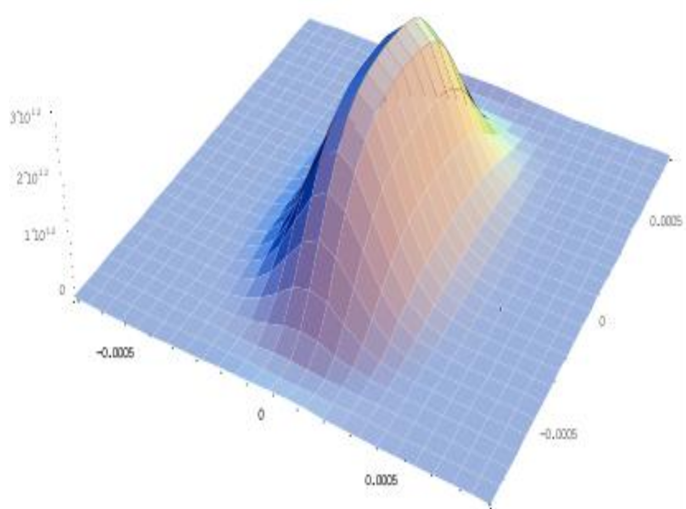
The "CHG" configuration



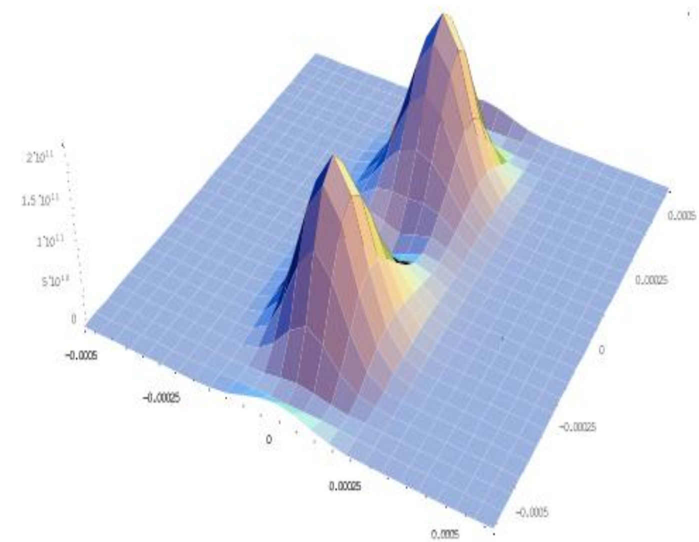
The "NHG" configuration



Angular distribution of harmonic emission

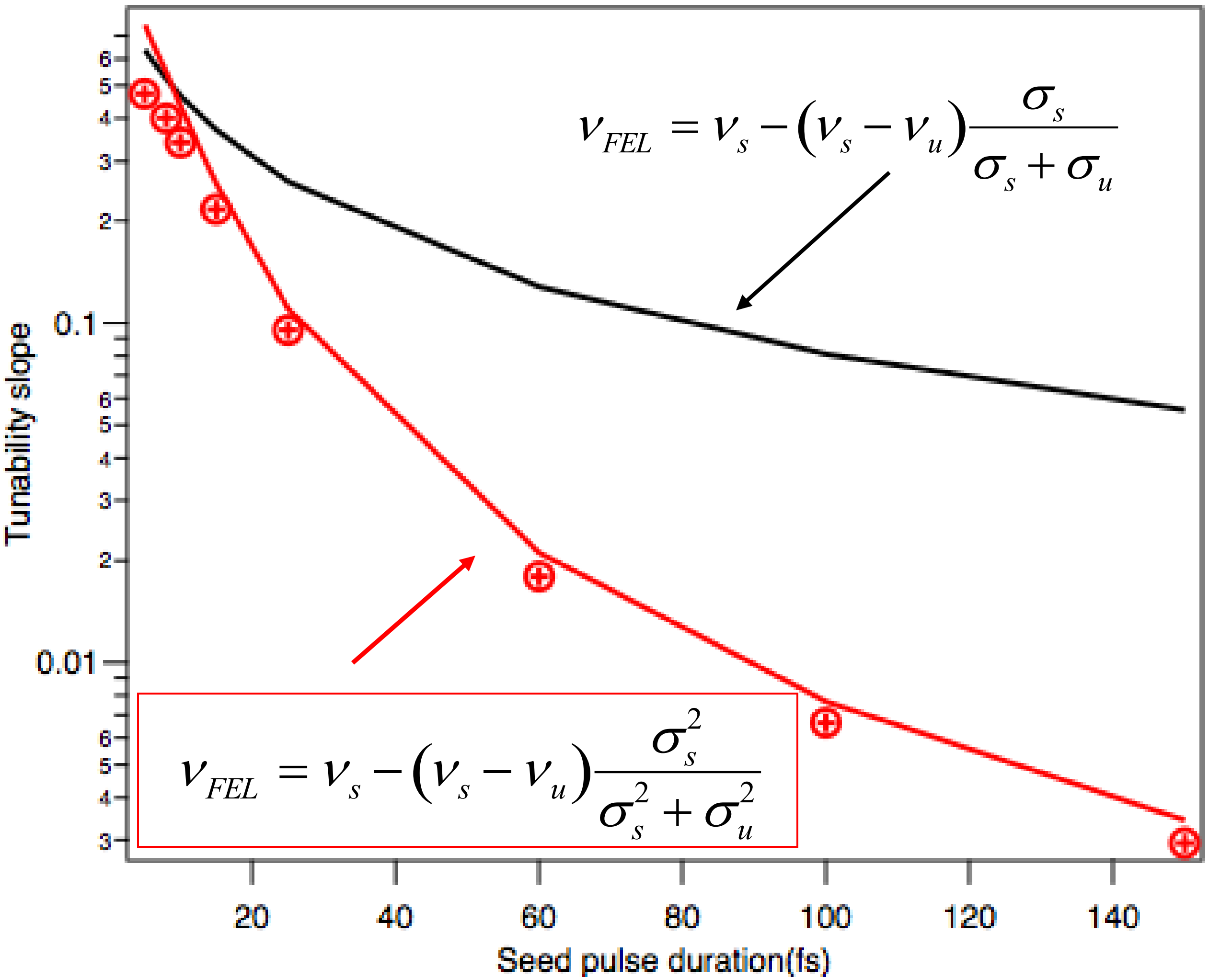


Angular distribution of ***circularly polarized*** *harmonic emission*



Frequency pulling in FEL's:
Numerical demonstration

Simulations using GINGER



E. Allaria, G. De Ninno, M.B. Danailov
*EPL **89** 64005 (2010)*

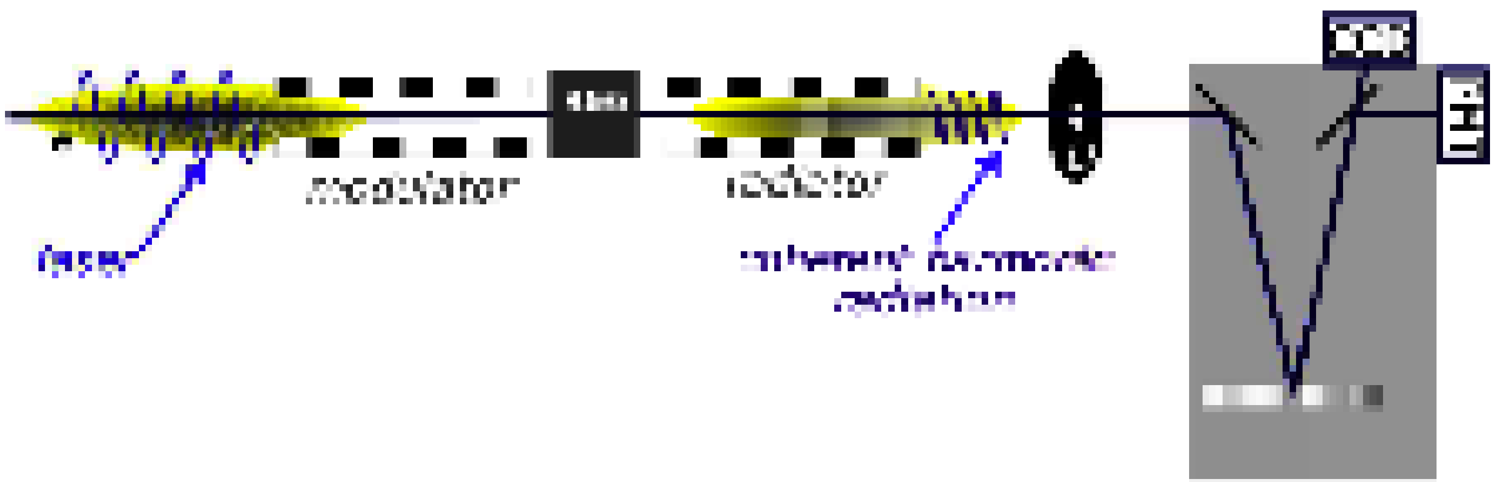
Characterization of out-of-axis harmonic emission
(motivation and experimental layout)

Motivation:

1) Characterize out-of-axis harmonic emission both in “CHG” and “NHG” configurations

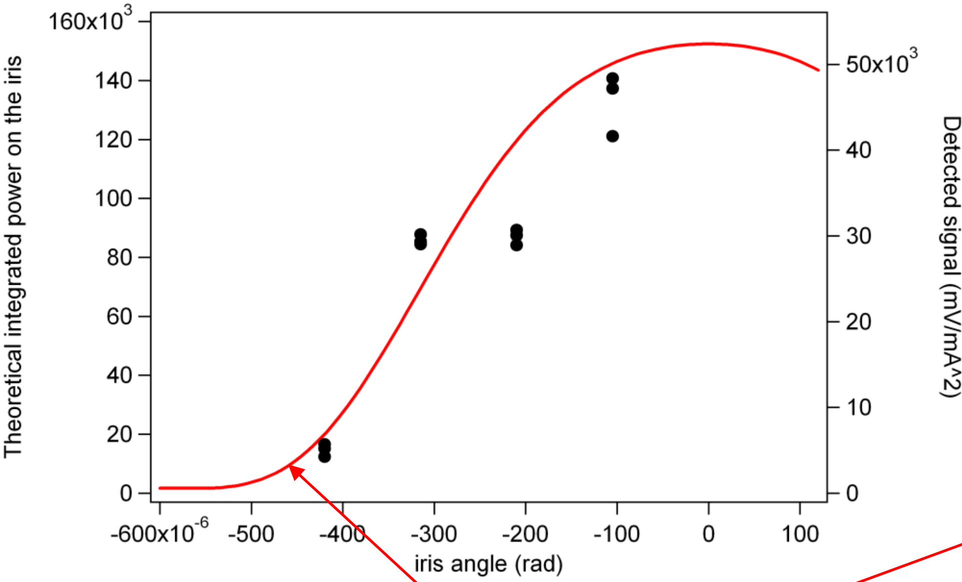
2) Benchmark theoretical calculations

Experimental layout

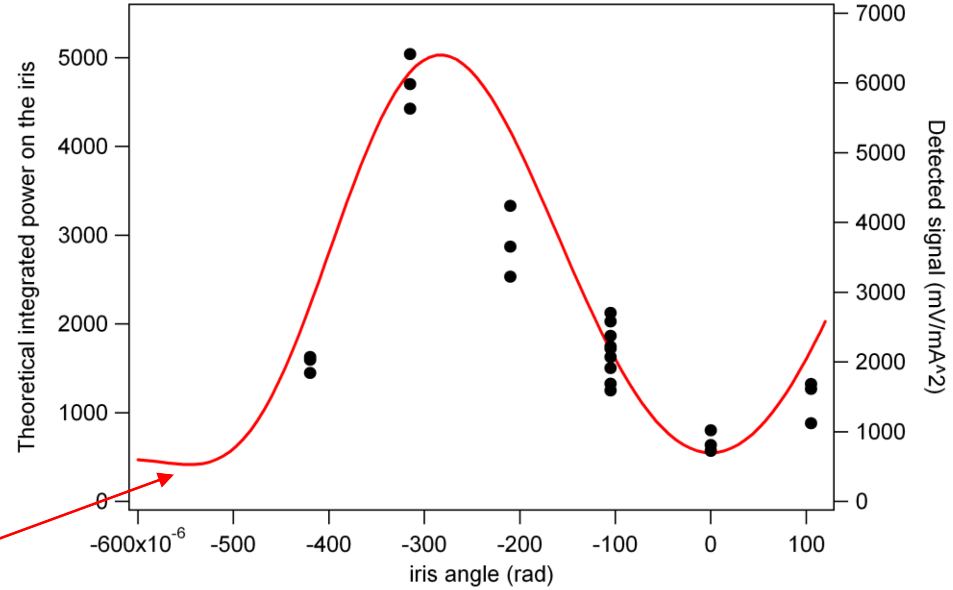


Characterization of out-of-axis harmonic emission
(Results)

CHG circular polarization (780 nm --> 260 nm)



CHG circular polarization (520 nm --> 260 nm)



Theory
(G. Geloni et al., *NIM A, 581, 856)*

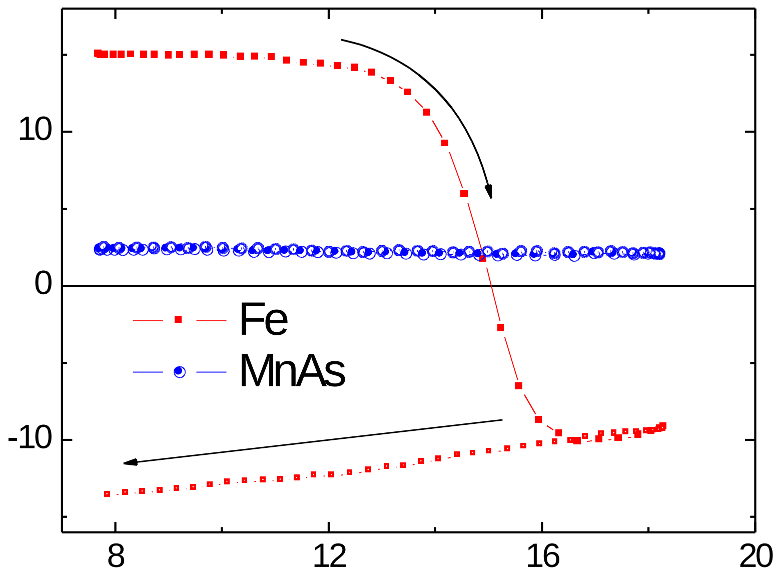
Good agreement with theory!

Next to do

Define the most appropriate pump power density conditions for effectively inducing transient phenomena without affecting the average sample temperature

Determine the time scale governing the formation and disappearance of the magnetic stripes in MnAs/GaAs(001)

X-ray resonant magnetic scattering experiments show that the magnetization direction of a thin Fe film deposited on MnAs/GaAs(001) can be fully reversed in a thermal cycle of a few degrees close to room temperature, **without making use of an external magnetic field**.



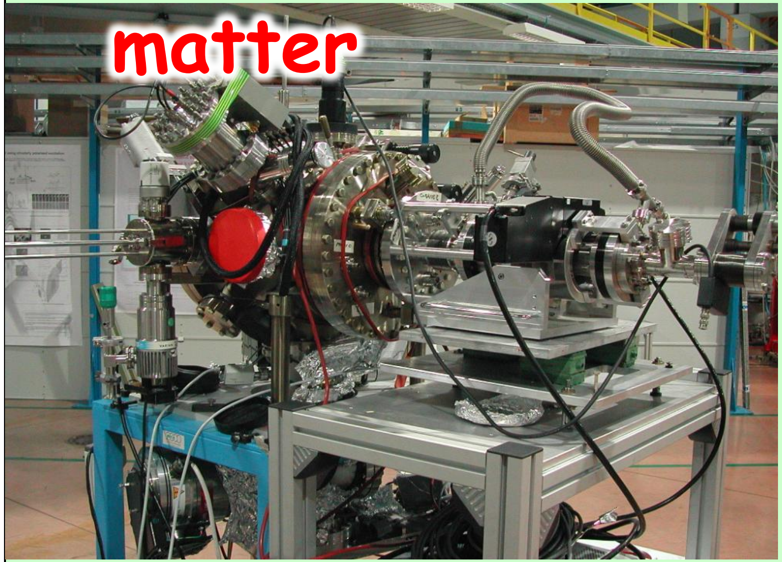
Local magnetization switching may be be obtained by using focused laser radiation.

Temporal aspects of the magnetization will be dictated by the dynamics of the appearance and disappearance of the stripes in the phase coexistence region.

Need for investigating the dynamical aspects of the stripe formation in MnAs/GaAs(001)

Pump-probe experiments in the fs regime

condensed matter



IRMA reflectometer

Maurizio Sacchi

CNRS and SOLEIL (Fr)

Recent activities

- **FEL physics:**

Tunability of a seeded free-electron laser through frequency pulling
(E. Allaria, M. B. Danailov, G. De Ninno, *submitted to Europhysics Letters)*

Characterization of out-of-axis harmonic emission

- **Source developments:**

CHG signal at 87 nm

Installation of an optical setup for pump-probe experiments

- **Test experiments:**

Time-resolved two-photon ionization on Acetylene

Time-resolved diffraction from self-organized stripe domains in MnAs/GaAs (001)

-Planning (1)

- 87 nm (2)

- off-axis harmonic radiation (3?)

- Setup (optical scheme + chambers) (1)

- Acetilene con Picco Marrazzo (2)

- MnAs/GaAs (001) (3?)

- Near future (compatibility, ThZ, femtoslicing, interreg projects) (1)

- Conculsions (test bench for FERMI but also…) (1)

Seed laser

Ti:Sapphire osc. + Reg. Ampli

Rep rate: 1kHz
λ: 780, 390, 260 nm
Peak power: 1-10GW
Pulse length: 100fs

Optical Klystron

2 Apple Undulators
Variable polarization
Dispersive section
Electromagnetic Modulator

Electron bunch (single bunch mode)

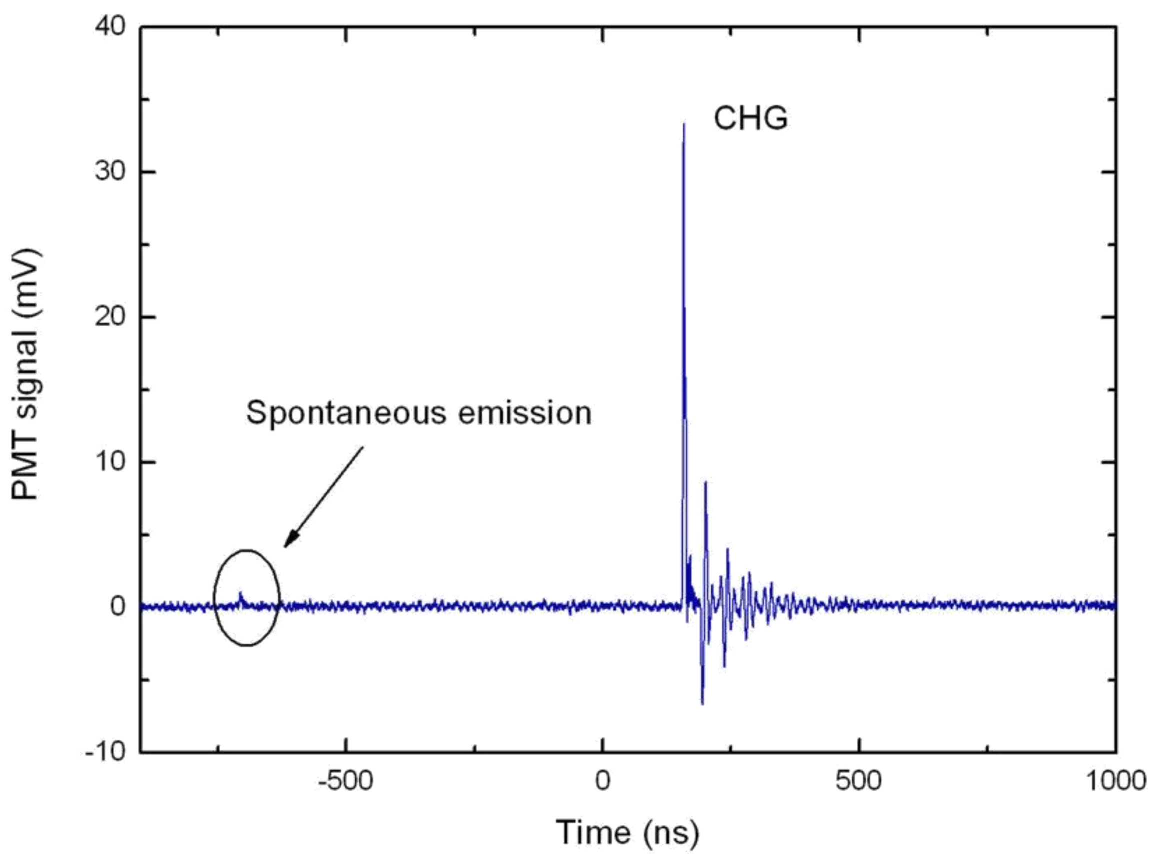
e^- energy: 0.75 – 1.1GeV
Rep rate: 1.157 MHz
Peak current: 10-50 A
Pulse length: 30ps
E spread: ~500keV

Expectation on 2nd and 3rd harmonics (photons per pulse)

$$\frac{\text{SR-CHG}}{\text{spontaneous emission}} = 100 \div 1000$$

First CHG evidence on 29 April 2007

- Seed @ 780 nm → CHG @ 260 nm (3rd harmonic)



e-beam

E_{beam} = 0.75 GeV

I_{beam} = 0.57 mA (single bunch)

rep. rate ~ 1 MHz

seed laser:

λ = 780 nm

pulse length ≈ 100 fs

pulse energy ≈ 2 mJ

rep. rate ~ 1 KHz

seed at 390nm + E_{beam} = 1.1 Gev

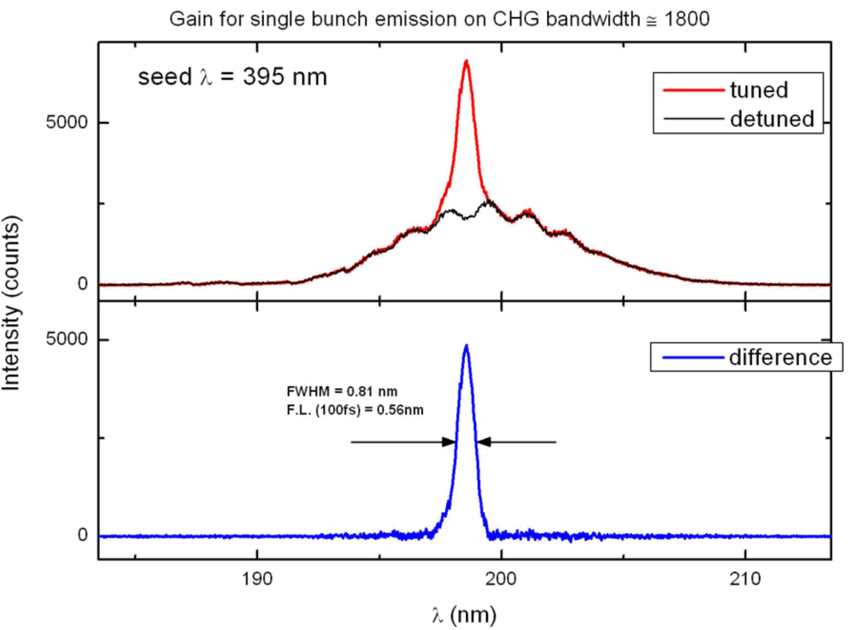
CHG

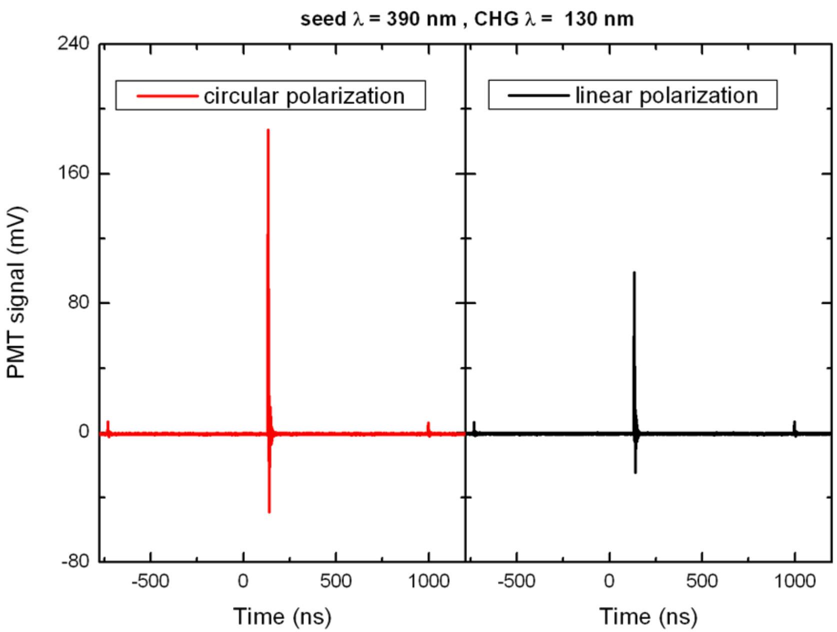
II harmonic

(6.2 eV)

III harmonic

(9.5 eV)





CHG spectra:

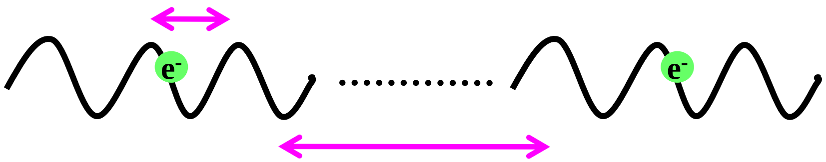
SB gain ~ 2000
$\Delta\lambda$: 1.4 Fourier limit

Variable polarization

Timing: Laser-bunch synchronization

Single bunch configuration

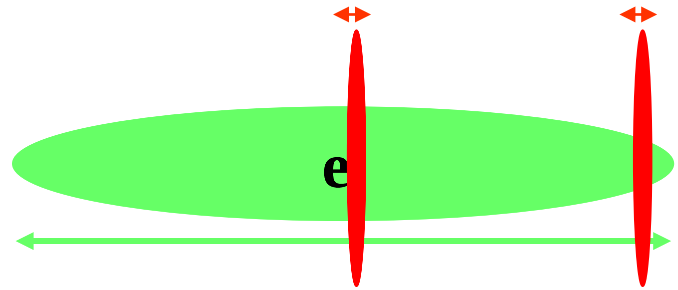
500 MHz – 2 ns **jitter ☜ 1.5 ps**



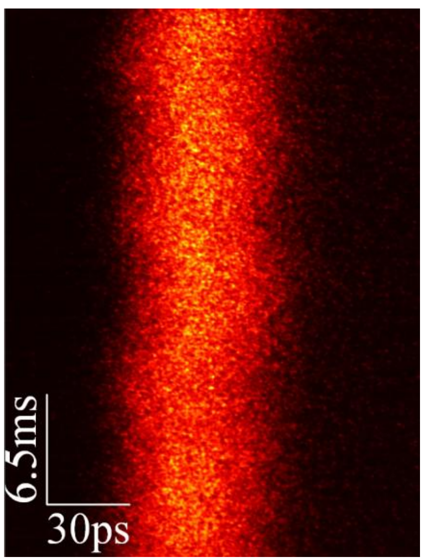
Single bunch Rep. Rate = 1.16 MHz – 864 ns

Seed laser

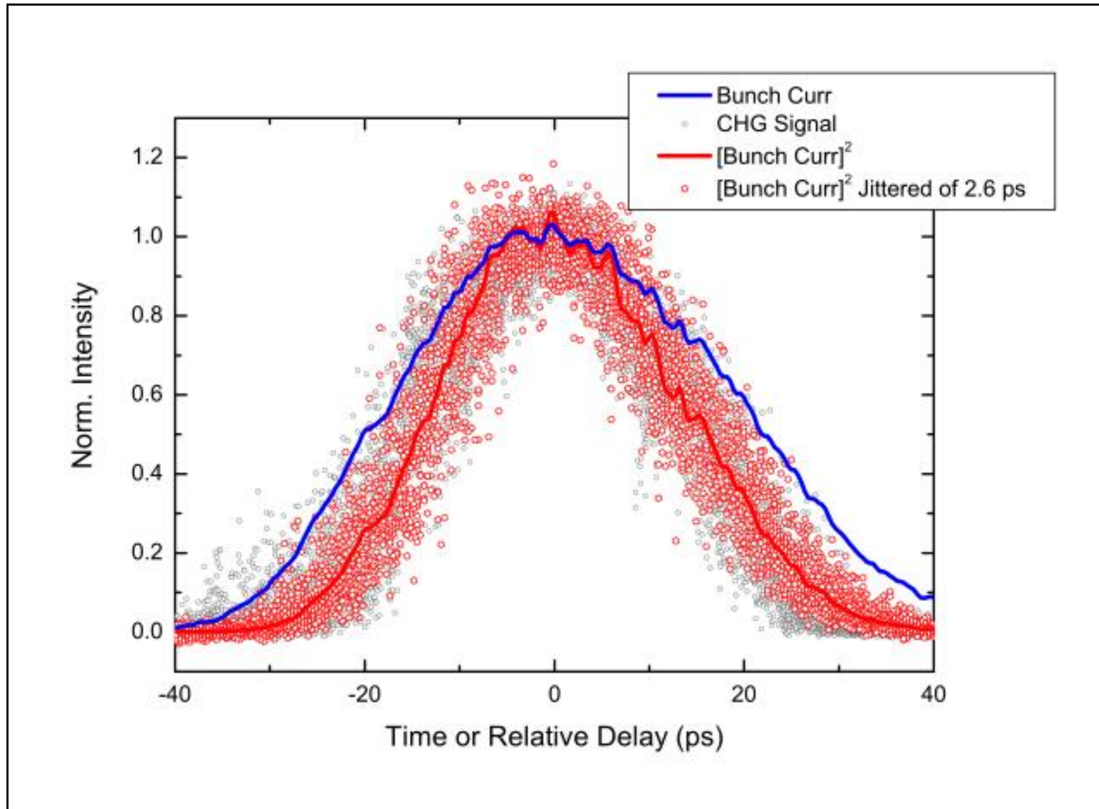
100÷200 fs



25 – 30 ps

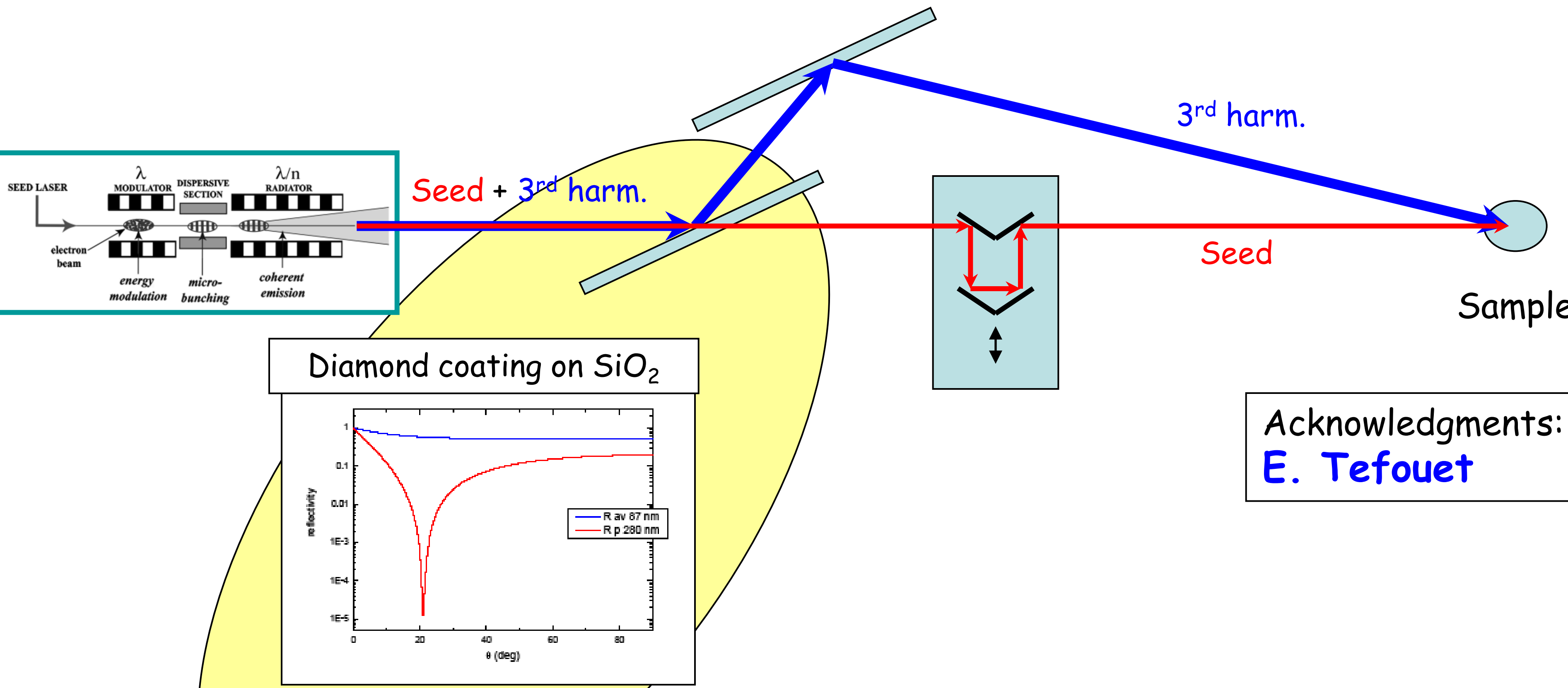


Streak camera acquisition
of spontaneous emission

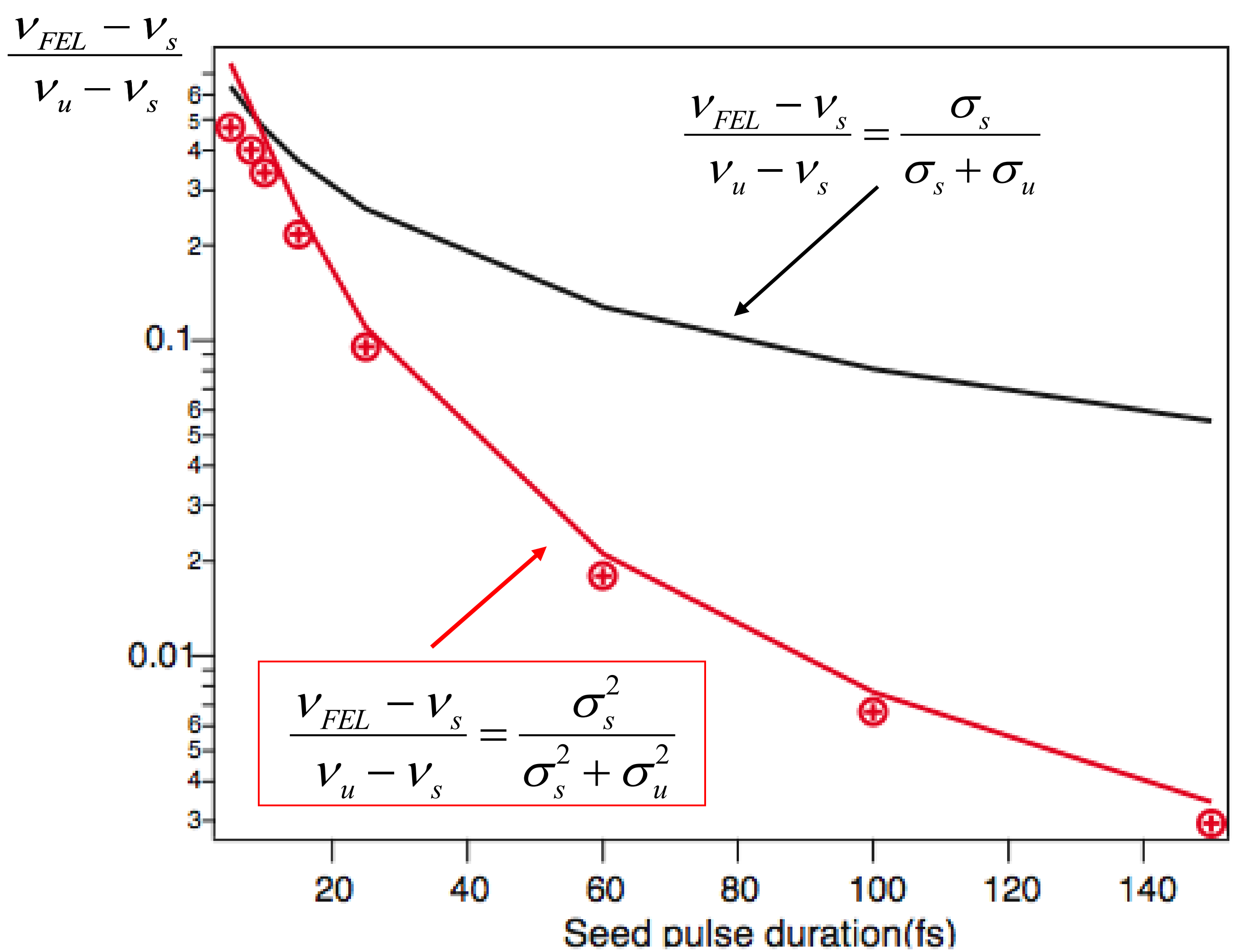


Pump & Probe scheme

- UHV beamline: NIM / Order Separator
- seed 260nm -> CHG 87nm (14.2 eV)



Acknowledgments:
E. Tefouet



$\frac{\nu_{FEL} - \nu_s}{\nu_u - \nu_s}$
6
5
4
3
2
0.1
6
5
4
3
2
0.01
6
5
4
3
$\frac{\nu_{FEL} - \nu_s}{\nu_u - \nu_s} = \frac{\sigma_s}{\sigma_s + \sigma_u}$
$\frac{\nu_{FEL} - \nu_s}{\nu_u - \nu_s} = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_u^2}$
20
40
60
80
100
120
140
Seed pulse duration(fs)

SF-FEL limits

Tunability
UHV beamline

BEAMTIME

Project Idea n. PI2008037

Title	**Storage–Ring Harmonic Generation at Elettra: obtain compatibility with 2–GeV user operation mode**
Cluster	**Elettra**
Proposer(s)	**G. De Ninno, M. Coreno, E. Allaria, C. Spezzani, E. Karantzoulis, M. Trovo‘, M. Danailov, L. Romanzin**
Objectives	**Demonstrate compatibility of Storage–Ring Harmonic Generation (SRHG) with standard user operation mode; perform pilot user experiments using the SRHG source.**

Description

After the successful implementation of SRHG at Elettra [1,2], the source is ready to be exploited for original user experiments. However, the lack of compatibility with the standard user operation mode makes the time available for experiments very limited. Within this project, we aim at demonstrating the full compatibility of SRHG with 2–Gev user operation mode. Such an achievement relies on the possibility of 1) tuning the first undulator (modulator) of the FEL beamline at 195 nm; 2) generating enough seed power at 195 nm. A recent set of measurements carried out by the U.O. Inserzioni [3] demonstrated 1). Experiments aimed at demonstrating 2) are currently ongoing at the Elettra laser laboratory. According to the first obtained results [4], reaching the minimum seed level necessary to perform HG at 2 GeV should not be an issue. However, increasing the seed power (i.e, improving HG performance) will require an upgrade of the seed laser system. On the base of the above, the most relevant hardware components needed to demonstrate the compatibility are: a) a new (13mm–gap, NEG–coated) vacuum chamber that should replace the old (17mm–gap) one, allowing the modulator to be tuned at 195 nm; b) a new laser pump allowing to increase the available seed power. During the project, we also plan to carry out some experiments aimed at characterizing and improving the source efficiency. This will require the purchase of a small diagnostic vacuum chamber. After the demonstration of SRHG in user–compatible operation mode, we will build a scientific case to be presented to SAC/MAC.

Duration

The project will last 24 months and will be divided in two subsequent phases.
During the first phase (M1–M18) we will demonstrate compatibility between SRHG and user operation mode at 2 GeV. In the meanwhile, we will carry out pilot experiments both at low (900 MeV) and high (2 GeV) energies.
During the second phase (M18–M24) we will continue experiments and build a scientific case to be presented to the SAC/MAC for the exploitation of the source in user compatible mode.

Estimated costs

– NEG–coated vacuum chamber with 13 mm internal gap: 20 keuro

– Diagnostic vacuum chamber: 15 keuro

– Upgrade of the seed laser system: 70 keuro

– Travels: 10 keuro

– Consumables: 10 keuro