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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

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Free Electron Lasers (II)

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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

Free Electron Lasers (II)

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Outline

-Basic concepts of light-electron interaction in a Free-Electron Laser
    -Why a free electron laser
    -How it work

- Different schemes for FEL
    -FEL aplifier
    -FEL oscillator
    -Self Amplified Spontaneous Emission FEL (SASE)
    -Coherent Harmonic Generation FEL (CHG)

- **Application to the FERMI project at Elettra**
- **Recent experimental results on the Elettra storage ring FEL**

The FERMI project at Elettra

(on behalf of the FERMI FEL group)

The FERMI project at Elettra

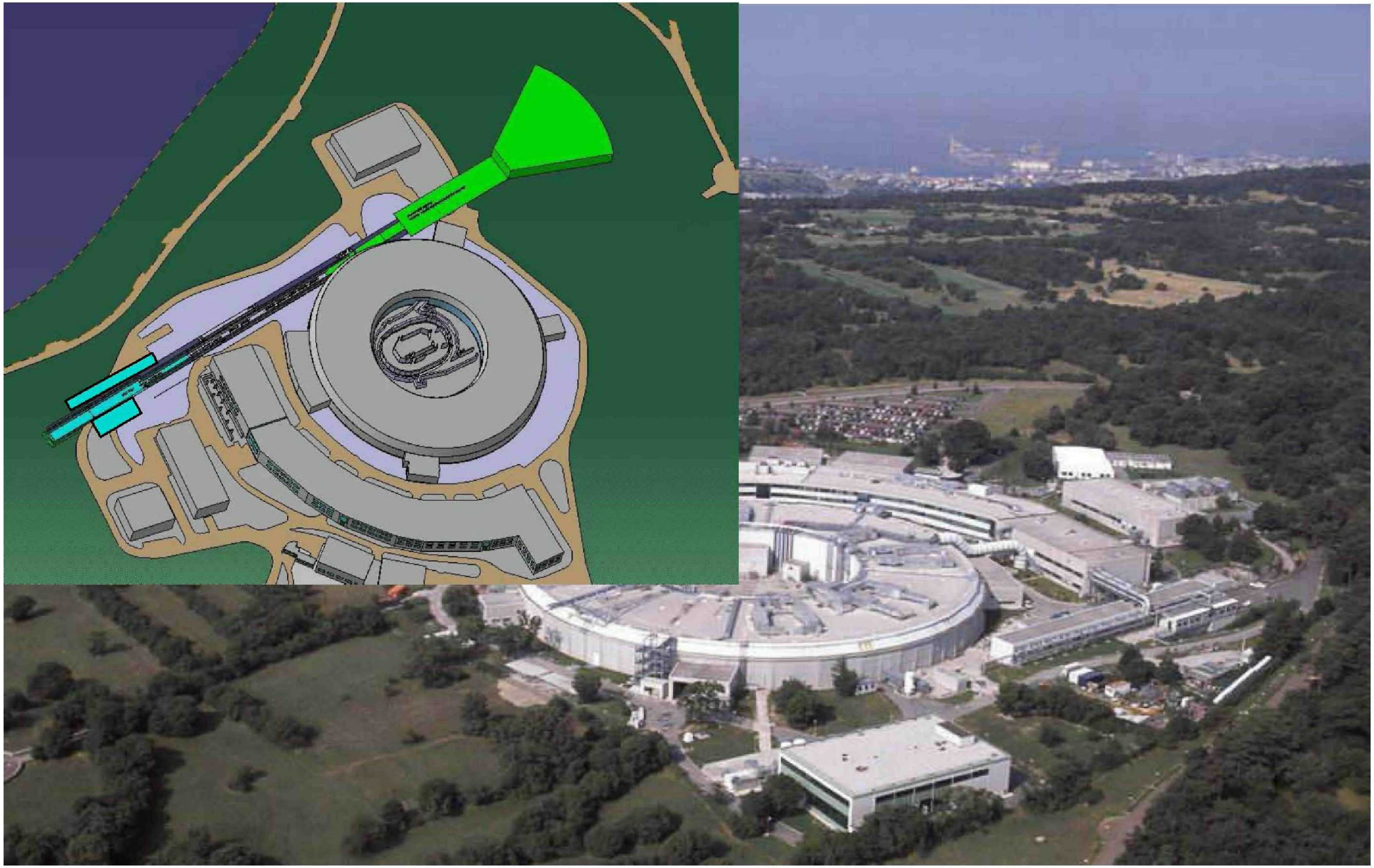
FERMI will be a photon source based on a multi-stage harmonic generation process. It will be one of the first FEL user facilities in the world operating at wavelengths in the VUV to soft X-ray range, based on the CHG scheme.

The project is making full use of the existing LINAC, previously used for the electron filling of the Elettra storage ring.

The FEL design is based on a “start-to-end” approach. This means that one has to keep track of the electron-beam dynamics and preserve its quality from the gun, through the LINAC, up to the end of the undulators chain.

This design and realization of a facility like FERMI relies on many different expertises: Accelerator and laser physics, electron and light diagnostics, high level engineering, ...

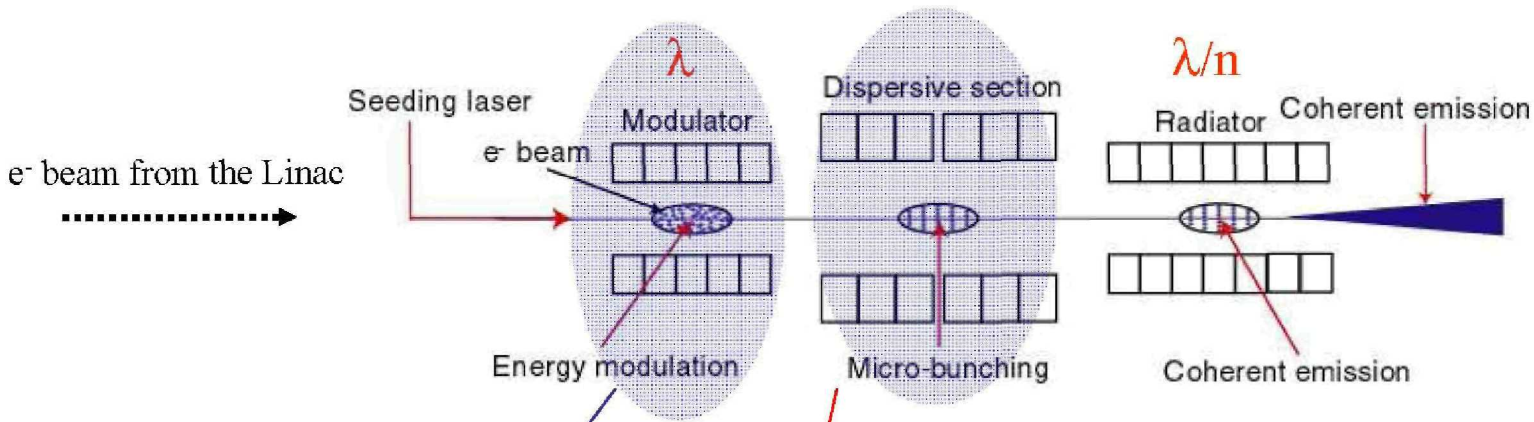
Overview of the ELETTRA laboratory



Outline

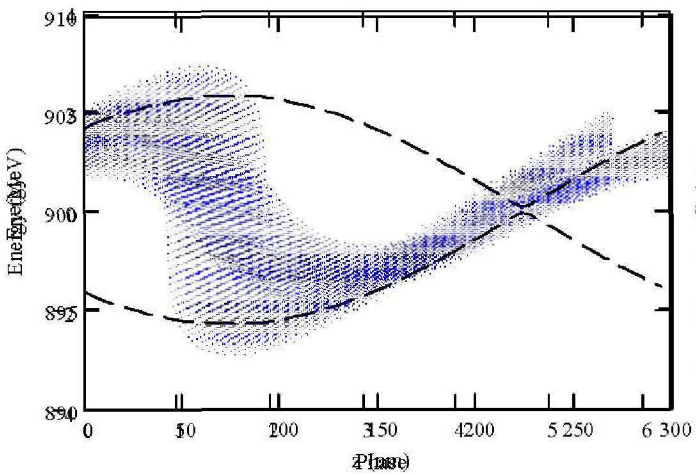
- Presentation of the two FERMI FEL's
- Numerical simulations for FEL 1 and FEL2
- Problem of FEL sensitivity to fluctuation of input parameters
- Discussion and open issues

Harmonic generation: the principle (1/2)

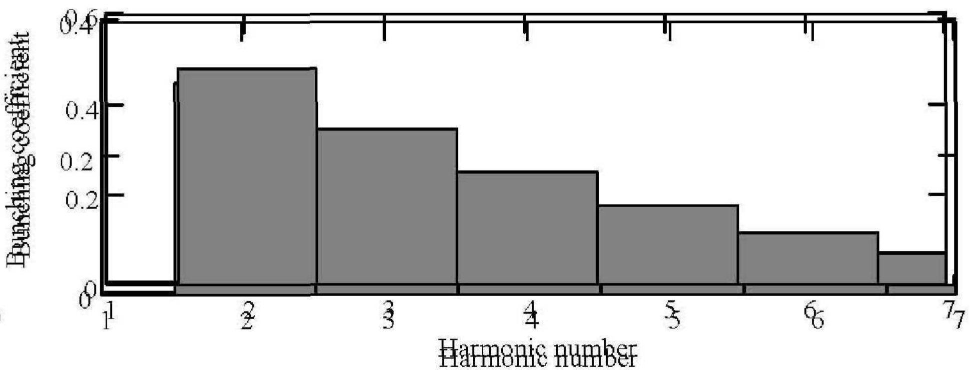


Modulator

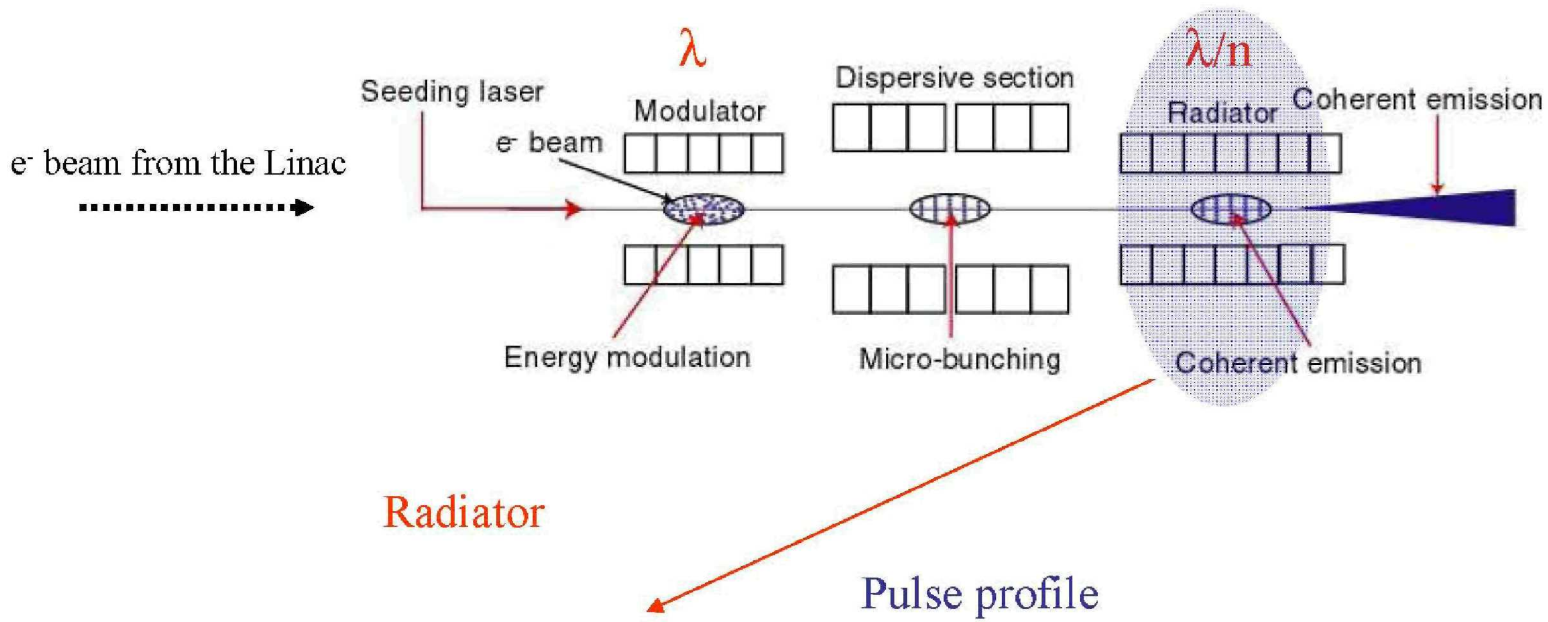
Dispersive section

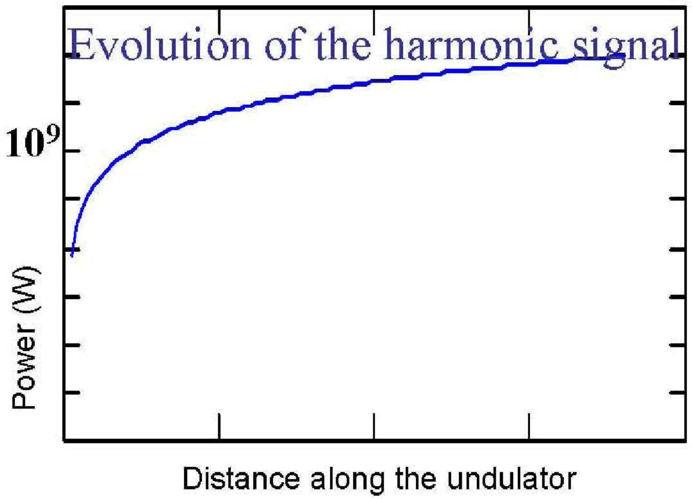


From Perseo,
a numerical code by L. Giannessi



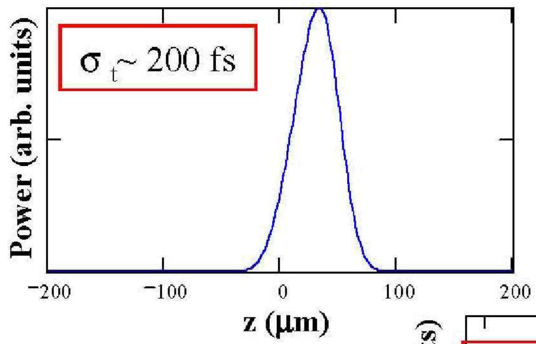
Harmonic generation: the principle (2/2)



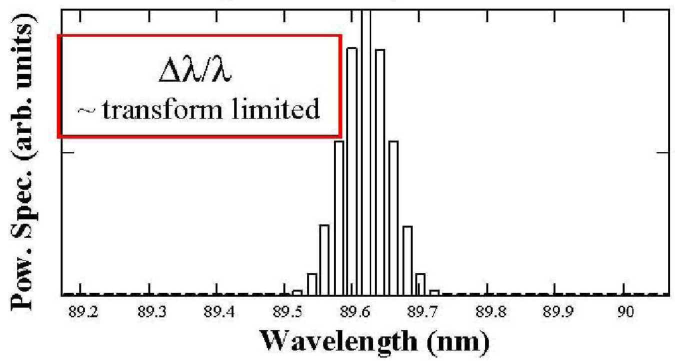


~ GW output signal

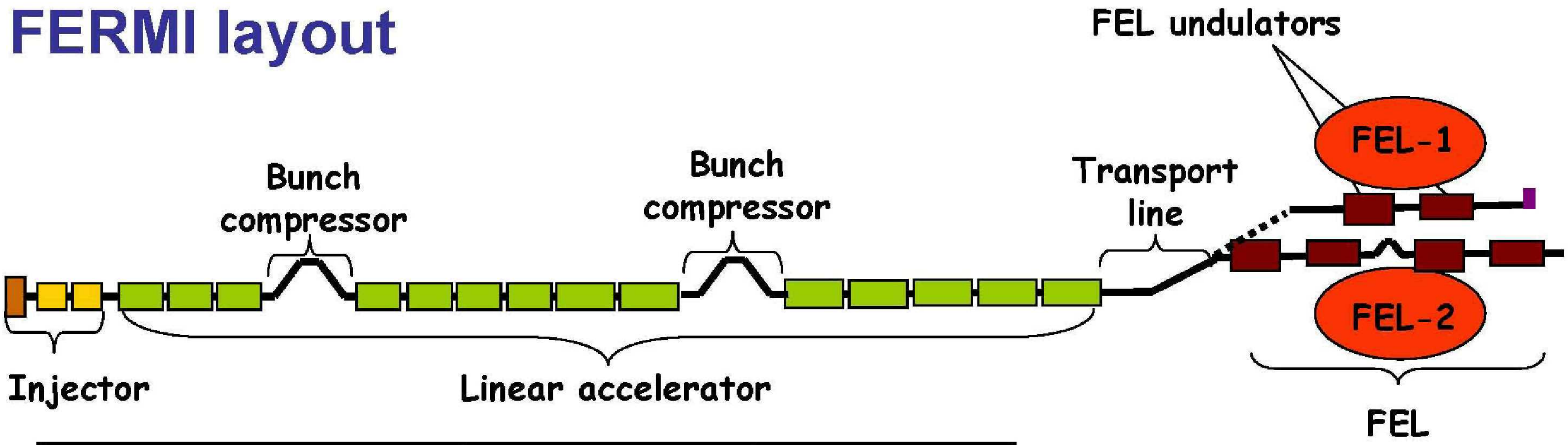
Pulse profile



Spectrum profile



FERMI layout



Parameter	*Medium bunch*	*Long Bunch*
Beam energy	1.2 GeV	1.2 GeV
Peak current	0.8 KA	0.5 KA
Uncorrelated energy spread	200 KeV	150 KeV
Normalized Emittance	1.5 mm·mrad	1.5 mm·mrad
Bunch length	~ 0.6 ps	~ 1.4 ps

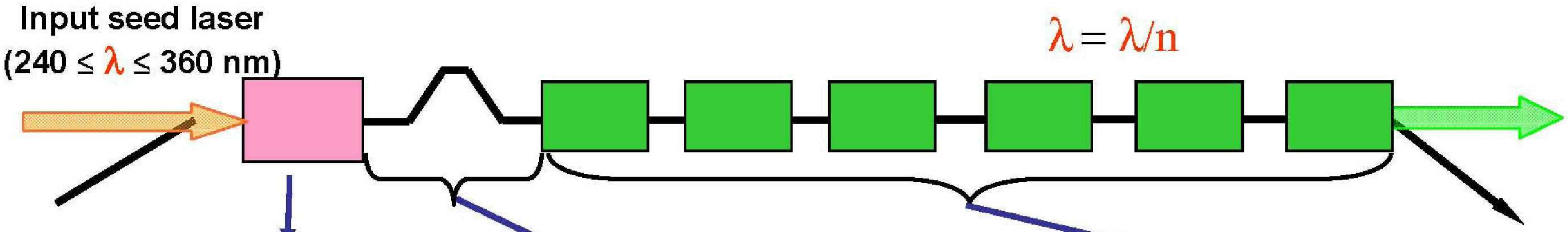
Two different ondulator lines for two different spectral regions:

- FEL-1 covers the spectral region between 100 and 40 nm
- FEL-2 the region between 40 and 10 nm

Both FEL's are based on the Harmonic Generation scheme and make use of APPLE II type ondulator for producing light with variable polarization

FEL-1 (100 - 40 nm)

Total length of FEL-1 ~ 23 m



Modulator

Parameter	*Value*
Type	Planar
Structure	One segment
Period	10 cm
K	>5
Length	3.04 m

Dispersive section

Parameter	*Value*
R_{56}	~ 32 μm
Length	~ 1 m

Radiator

Radiator	*Value*
Type	Apple
Structure	~ 6 Segments
Period	6.5 cm
K	2.4 - 4
Segment length	2.34 m
Break length	1.06 m
Total length	19.34 m

Electrons interact with an external laser field in the first ondulator, the energy modulation produced by this interaction is transformed into spatial modulation (bunching) to the laser wavelength and to its harmonics.

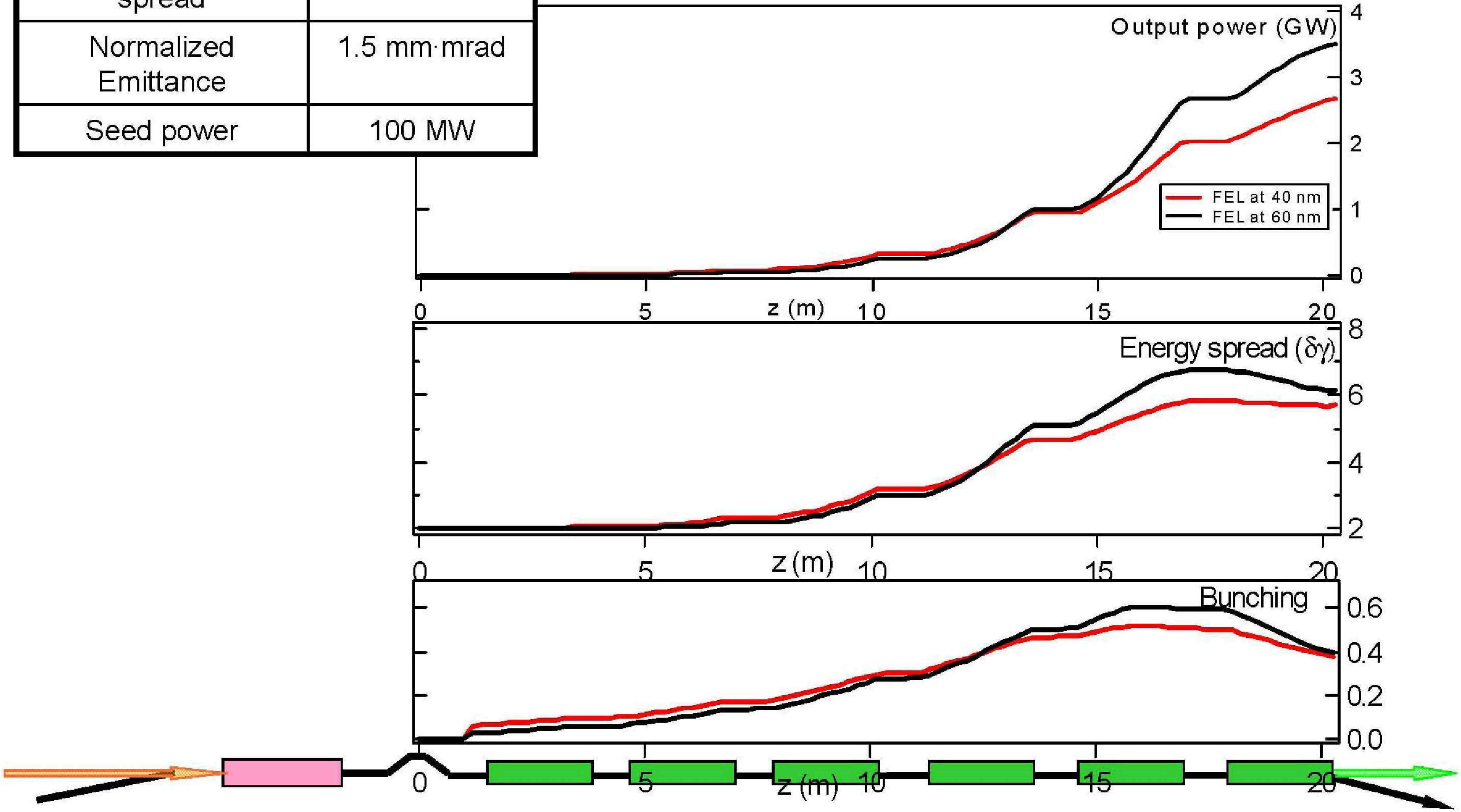
Bunched electrons emit coherently into the radiator tuned to the desired harmonic and FEL process is initiated.

A segmented radiator allows to insert electron optics and diagnostics between modules .

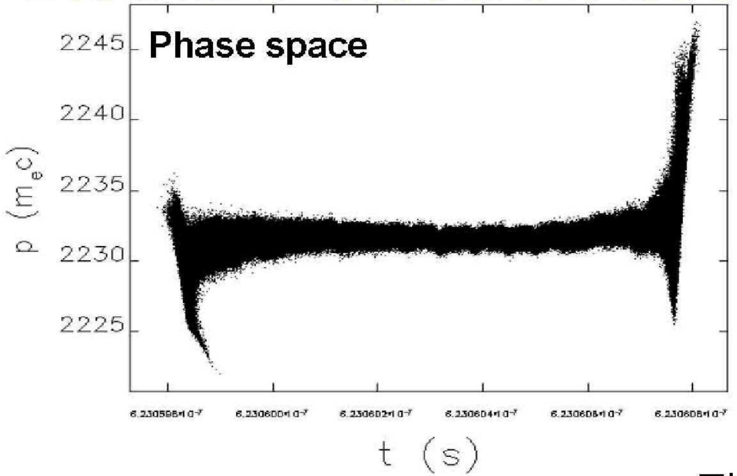
FEL-1 time independent simulations

Input parameters	*Medium bunch*
Beam energy	1.2 GeV
Peak current	0.8 KA
Uncorrelated energy spread	200 KeV
Normalized Emittance	1.5 mm·mrad
Seed power	100 MW

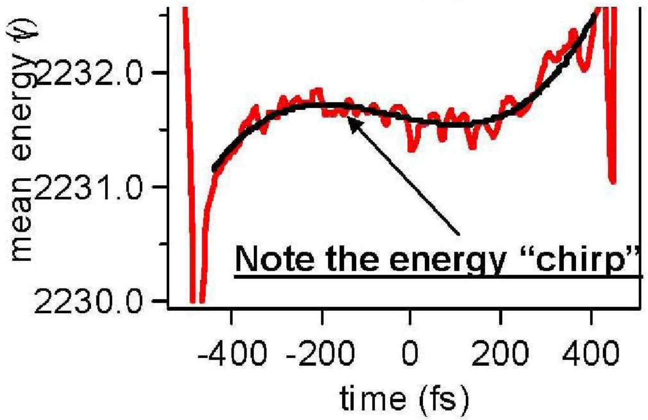
Within such approach we use ideal electron bunches whose parameters are those predicted for the FERMI Linac. Simulations show the possibility to reach saturation and output power of several GW within 6 radiator segments for the considered wavelength range (100-40nm).



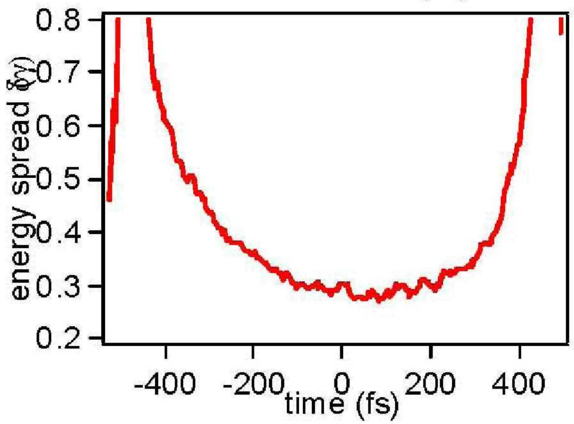
Medium electron beam at the end of the LINAC

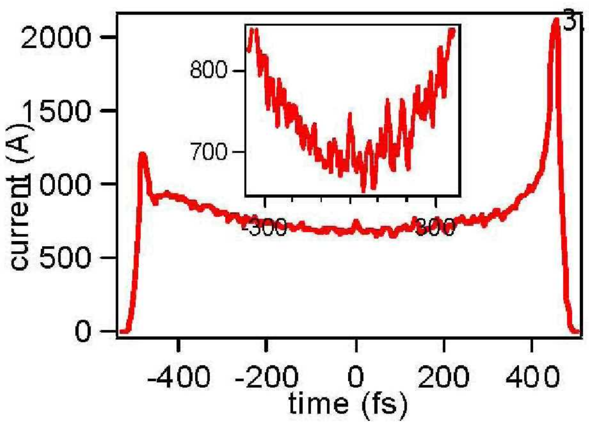


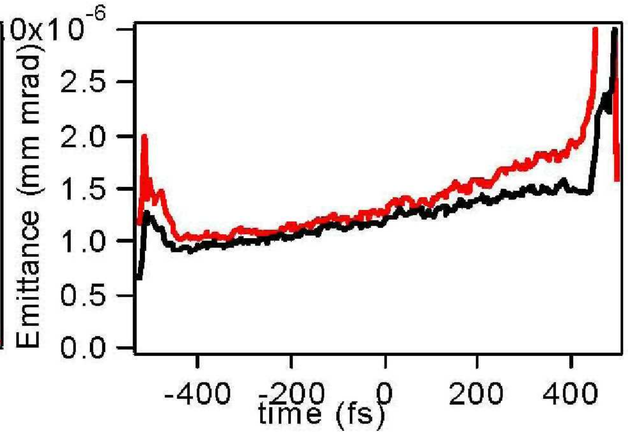
Parameter	*Value*
Beam energy	1.2 GeV
Peak current	0.8 KA
Uncorrelated energy spread	150 KeV
Normalized Emittance	1.5 mm·mrad
Bunch length (flat part)	~ 0.6 ps



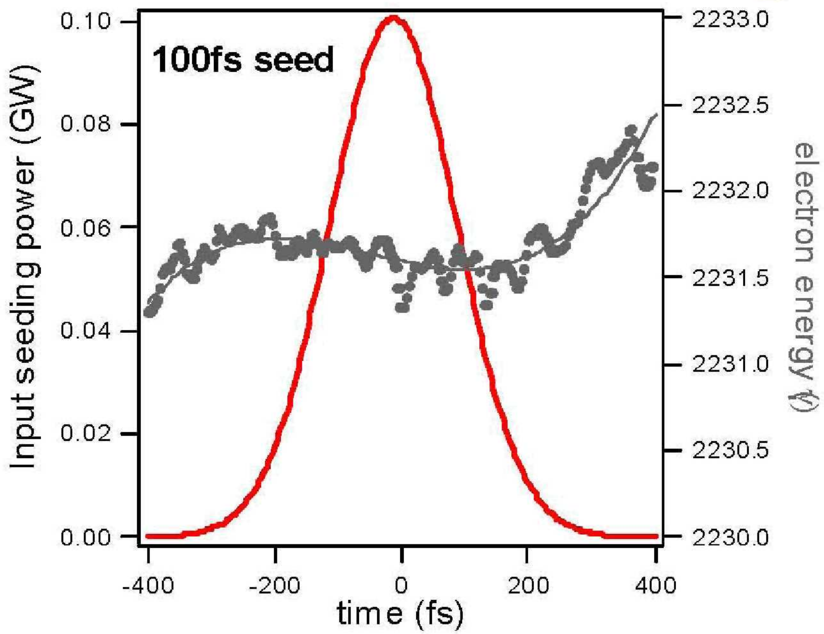
The analysis of the electron bunch shows the presence of a cubic chirp in the electron-energy profile with some noisy modulation period of the order of 10 μm. Similar microbunching modulation has been found also in the current profile.

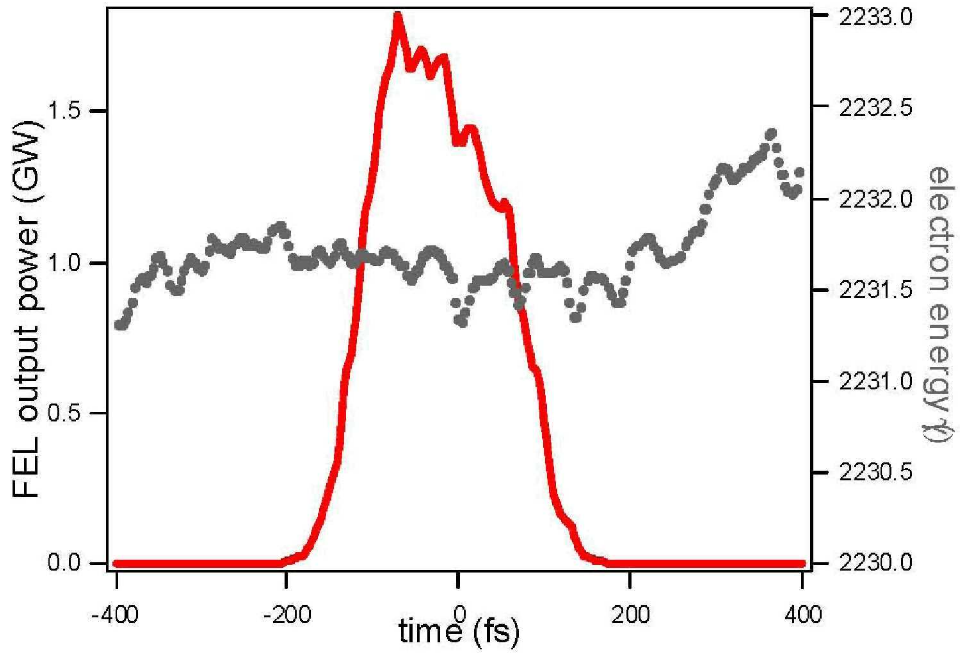




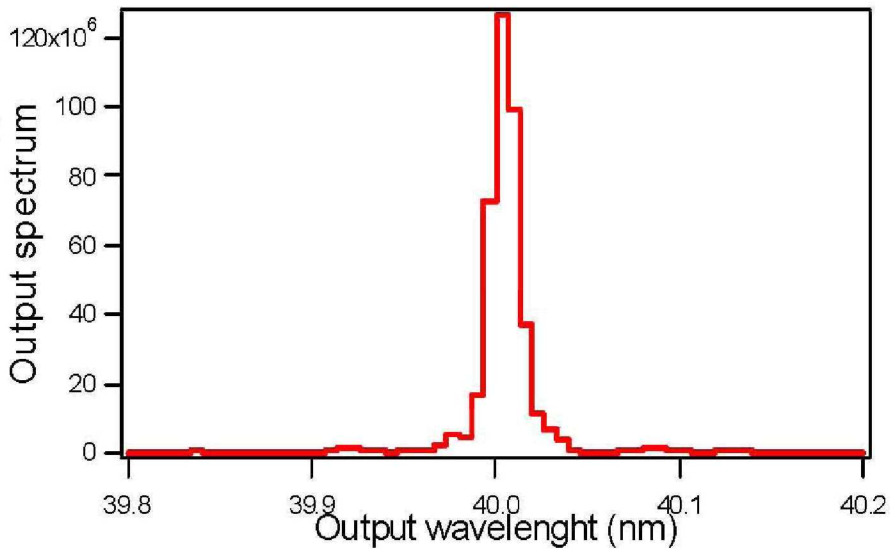


FEL1 simulation using medium bunch (40nm)





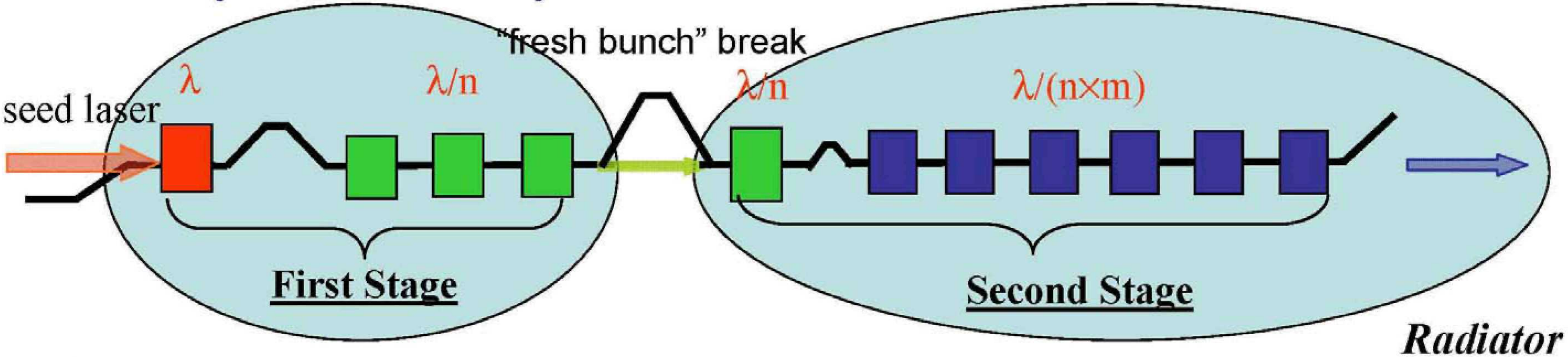
- The particle file has been simulated with the optimized setup for FEL1 using a seed pulse of 100fs rms centred on the flat part of the bunch.
- This produces an output pulse of the order of 1.5 GW and less than 70 fs long.
- The cubic chirp and the microbunched structure in electron energy profile are responsible for the increase of the bandwidth with respect to the Fourier limit.

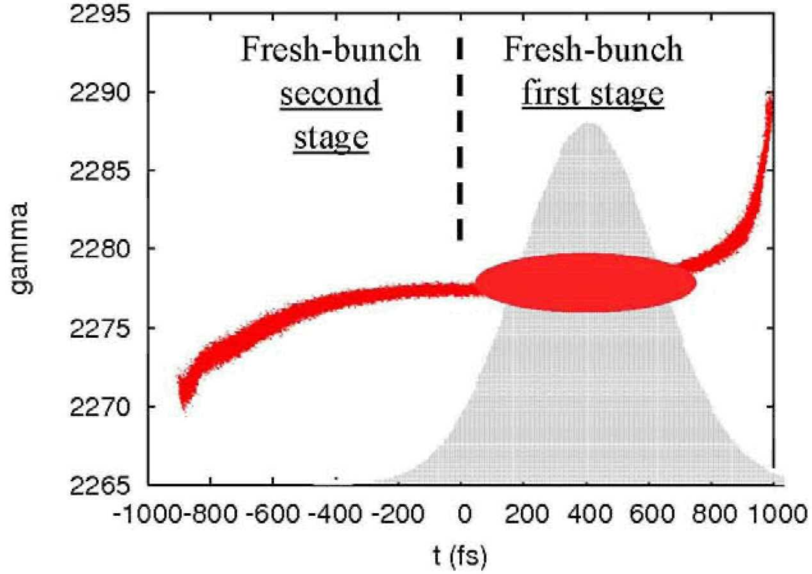


Pulse width (rms) = 66 fs
Photon number = 6.5e+13
Bandwidth (%) = 0.03
Ratio to Fourier limit = 1.9

FEL-2 (40 - 10 nm)

Total length FEL-2 ~ 37.5 m





Radiator

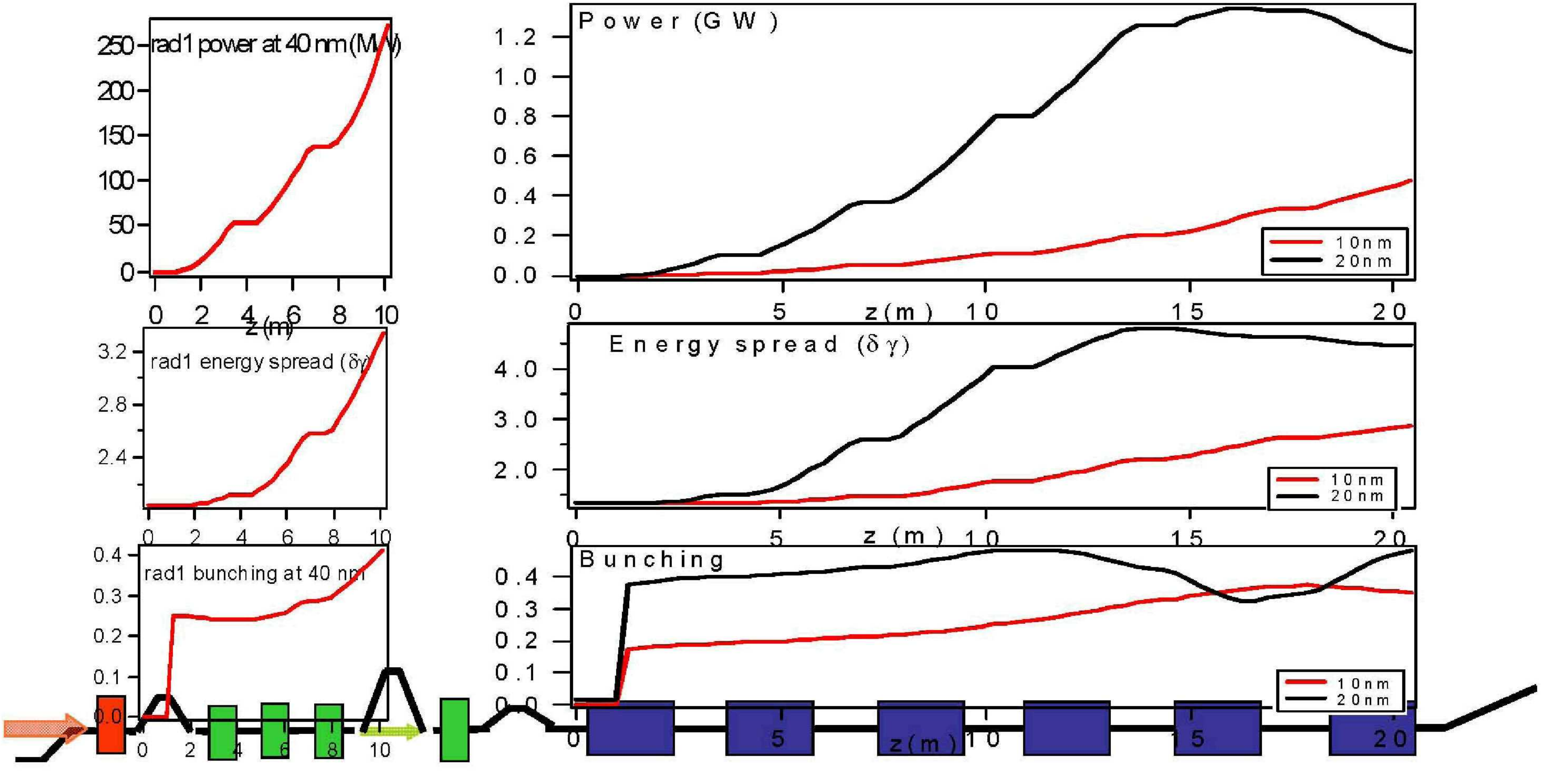
Parameter	*Value*
Type	Apple
Structure	Segmented
Period	5 cm
Segment length	2.4 m
K	1.1 - 2.8
Break length	1.06 m
Total length	19.7 m

- The electrons that are used for the first stage are not useful in the second stage because they have a too large energy spread.
- A fresh bunch break is used in order to delay the electrons with respect of the photons
- In the second modulator the produced 40 nm radiation is superposed to a fresh part of the electron bunch and a new harmonic generation is performed

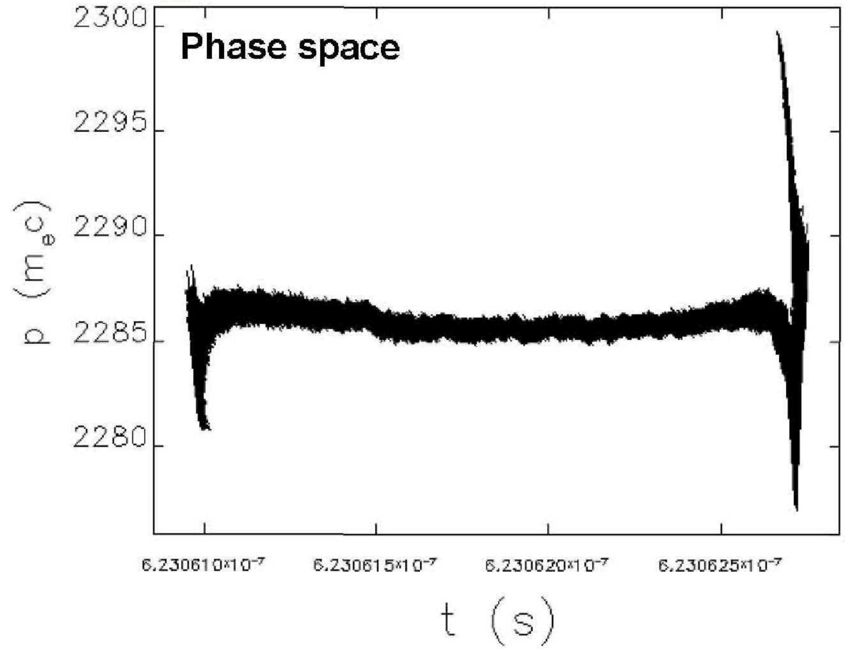
FEL-2 time independent simulations

Beam parameters	*Medium bunch*
Beam energy	1.2 GeV
Peak current	0.5 KA
Uncorrelated energy spread	150 KeV
Normalized Emittance	1.5 mm·mrad
Bunch length	1.4 ps

- Simulations show the possibility of reaching saturation within the 20 meter of radiator for the 20 nm case with more than 1 GW of output power.
- In the 10 nm case saturation is not reached within the six modules however ~ 500MW are obtained.



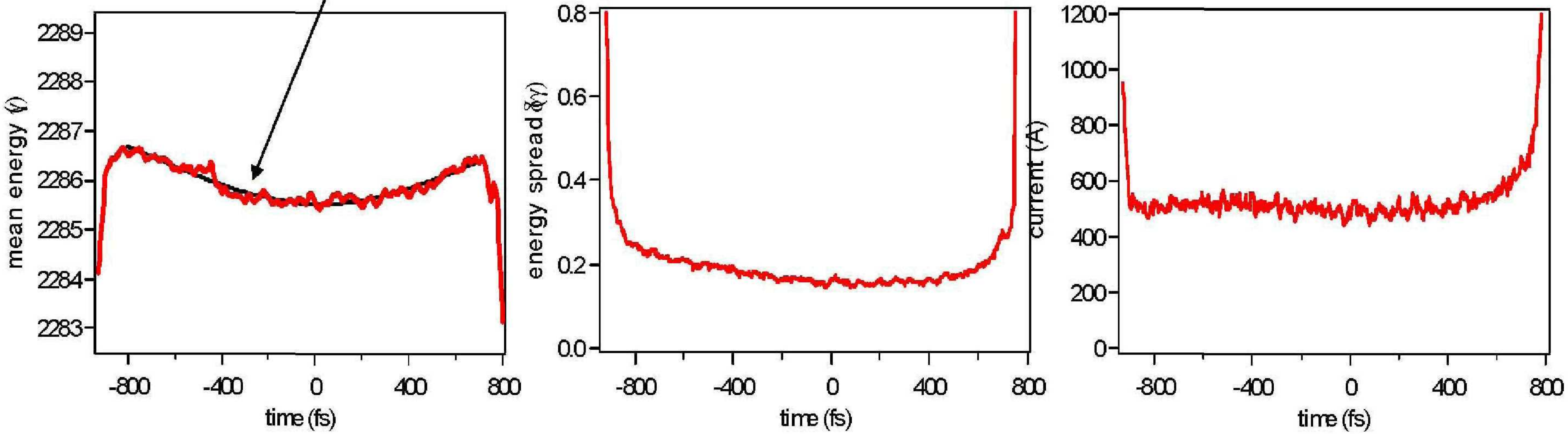
Long electron beam at the end of the LINAC



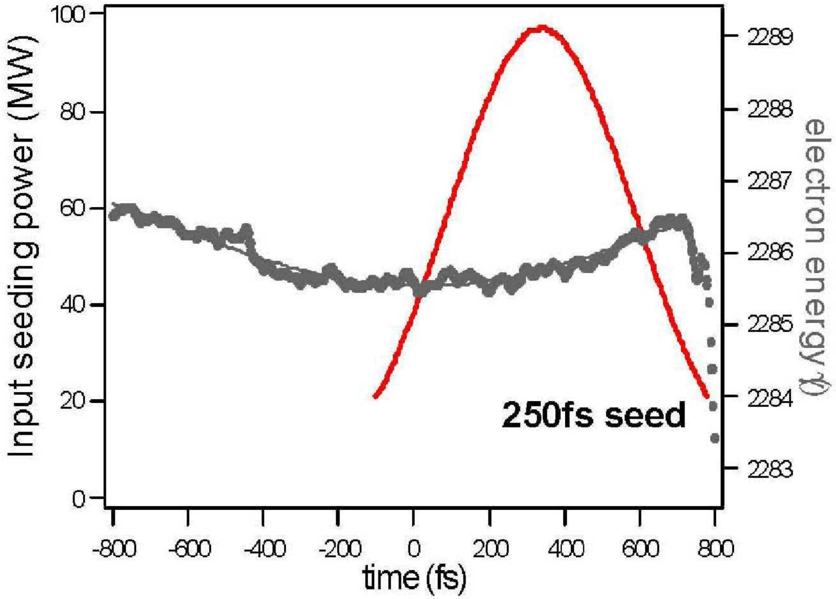
Parameter	*Value*
Beam energy	1.2 GeV
Peak current	0.5 KA
Uncorrelated energy spread	100 KeV
Normalized Emittance	1.5 mm·mrad
Bunch length	1.4 ps

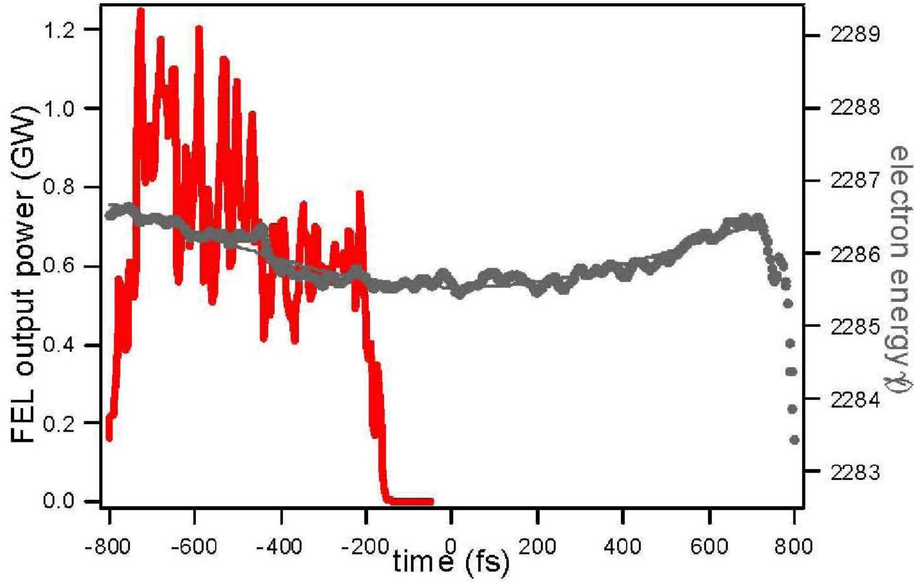
- The longitudinal phase space presents a quadratic chirp and residual fast time fluctuations of the mean energy.
- The useful part of the bunch is about 1.4 ps long and presents an energy spread which is of the order of 100keV. The current is of the order of 0.5 kA.

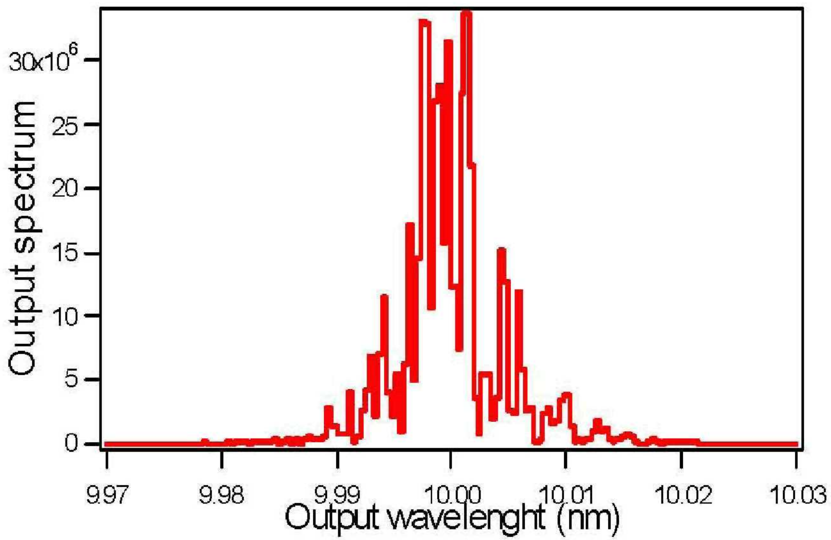
Note the energy "chirp"



FEL2 simulation using the long bunch (10nm)







- The length of the electron bunch allows the use of a seed pulse of 250 fs rms placed on the tail of the bunch.
- After the cascade the 10nm coherent emission is produced from the head of the bunch.
- Energy chirp and microbunching lead to a broadening of the bandwidth.

Pulse width (rms)	= 170 fs
Photon number	= 2.2e+13
Bandwidth (%)	= 0.04

Jitter on initial conditions

Studies of <u>output power sensitivity</u> to input jitter

(*e.g.*, ***energy, emittance, energy spread, peak current, seed power, beam offset*** *and* ***tilt***)

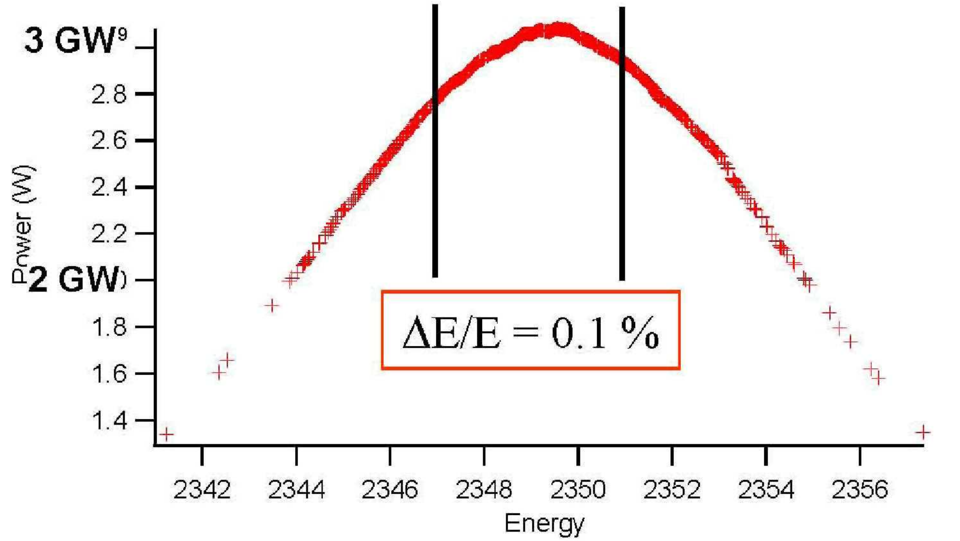
Series of time independent simulation runs have been performed varying imput parameter of the electron bunch as predicted from Gun and Linac studies.

Parameter	*Shot-to-shot variation (rms)*
Emittance	10 %
Peak current	8 %
Mean energy	0.1 %
Energy spread	10 %
Seed power	5 %
e-beam axis offset	100 μm
e-beam tilt	10 μrad

Simulations show a critical sensitivity to the electron mean energy responsible of strong fluctuations of the output power

FEL 1 at 100 nm
time independent simulations

Input mean energy is varied ONLY
All other parameters assumed constant
=> Global output power standard deviation: **9.6%**

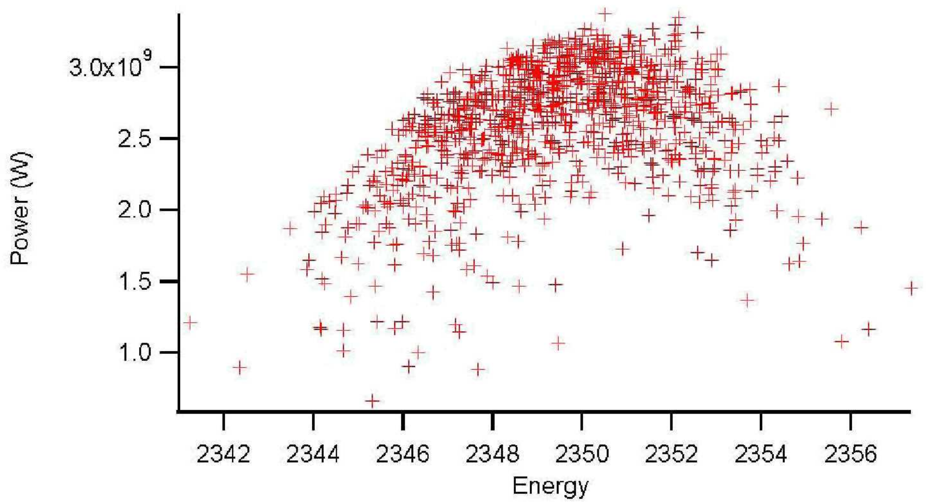


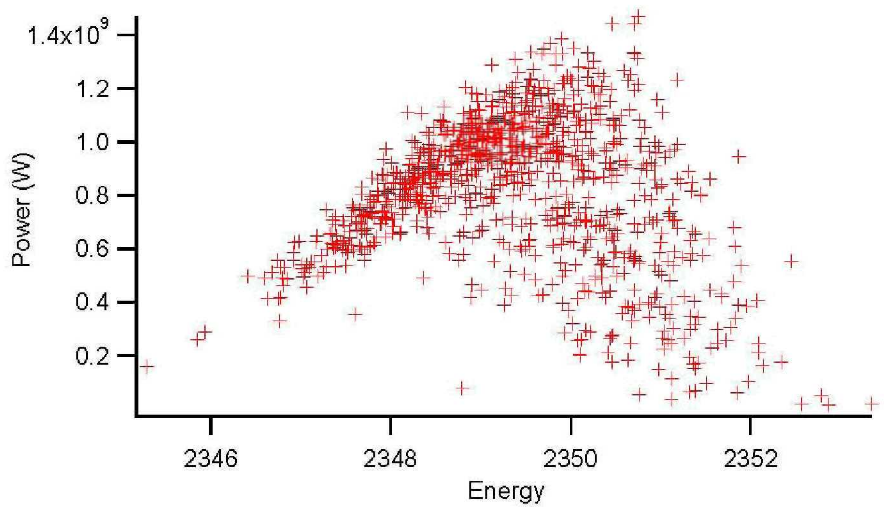
Simultaneous multi-parameter variation

Simultaneous variation of the following parameter has been considered :
energy, current, uncorrelated energy spread, transverse emittance, initial transverse position and tilt

FEL 1 at 100 nm
Energy variation projection
Output power global standard deviation: **16.5%**

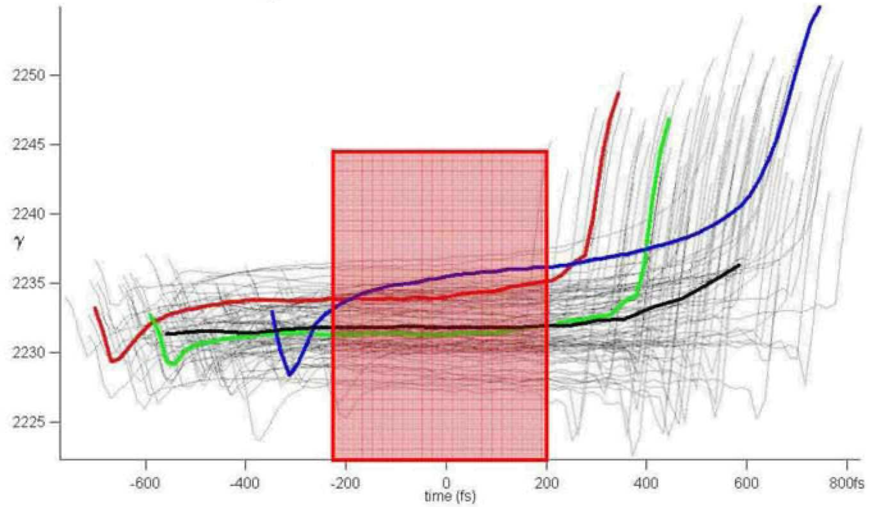
FEL 2 at 40 nm
Energy variation projection
Output power global standard deviation: **33%**

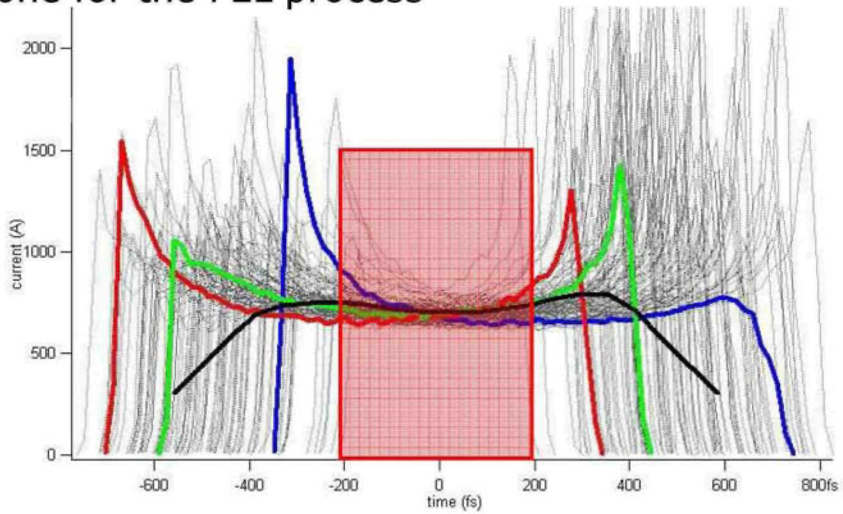


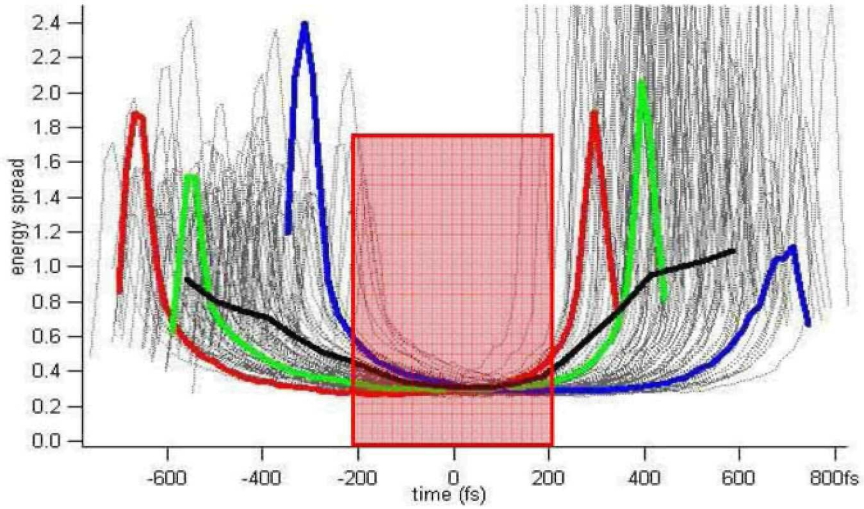


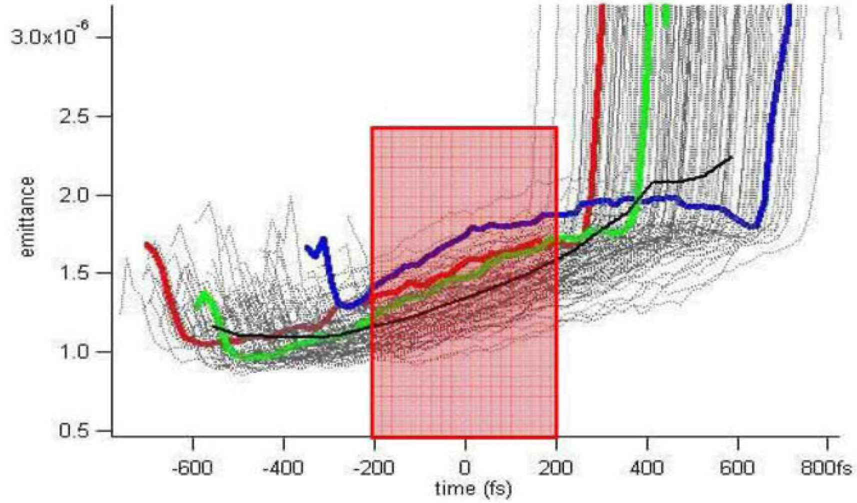
Simulation of 100 jittered electron bunches

- 100 electron bunches have been propagated starting from the Gun through the Linac considering possible noise sources (timing, phase and amplitude jitters)
- The study has been performed for the "Medium bunch" Linac configuration used for FEL1
- The central part has been considered as the useful one for the FEL process

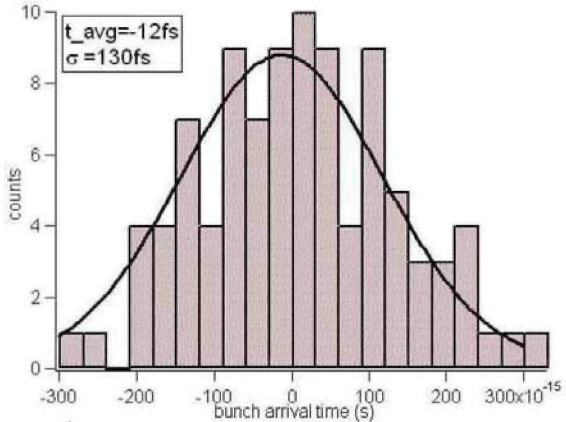


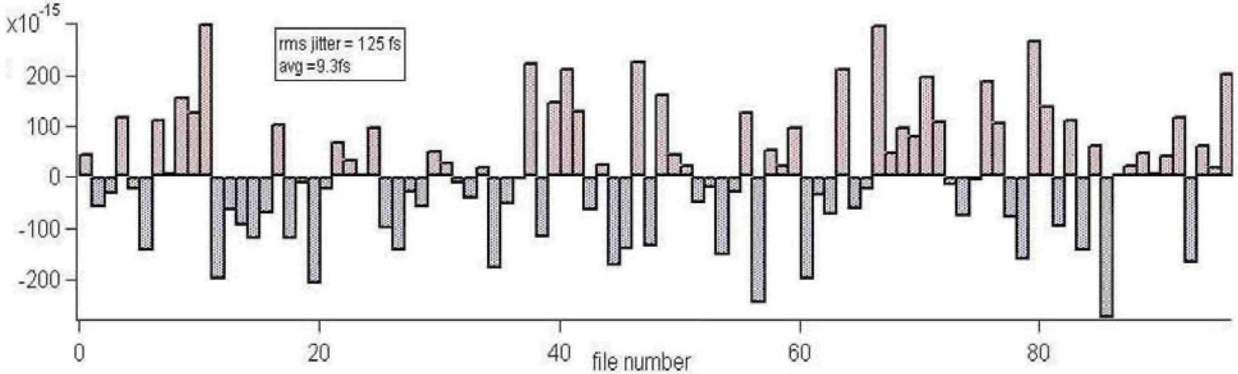


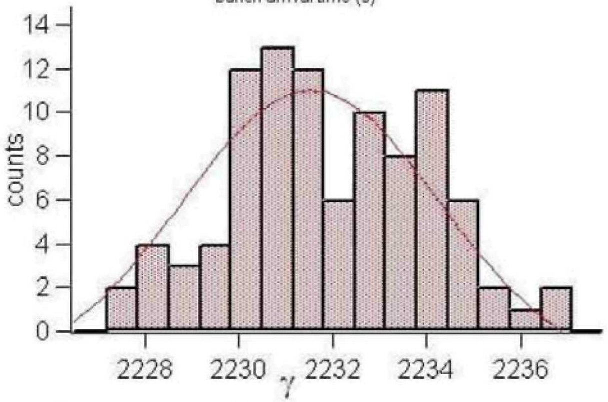


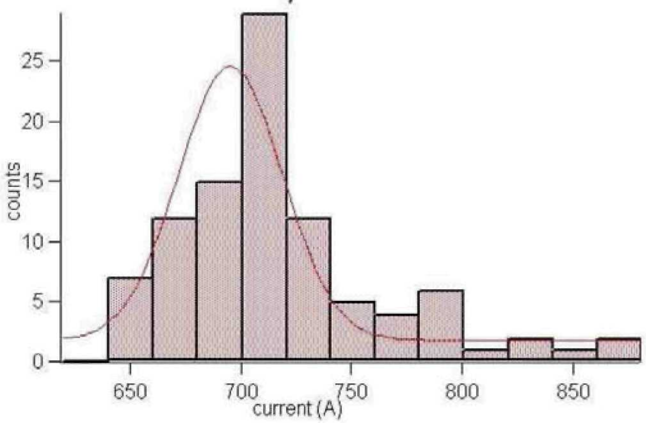


Analysis of 100 jittered electron bunches







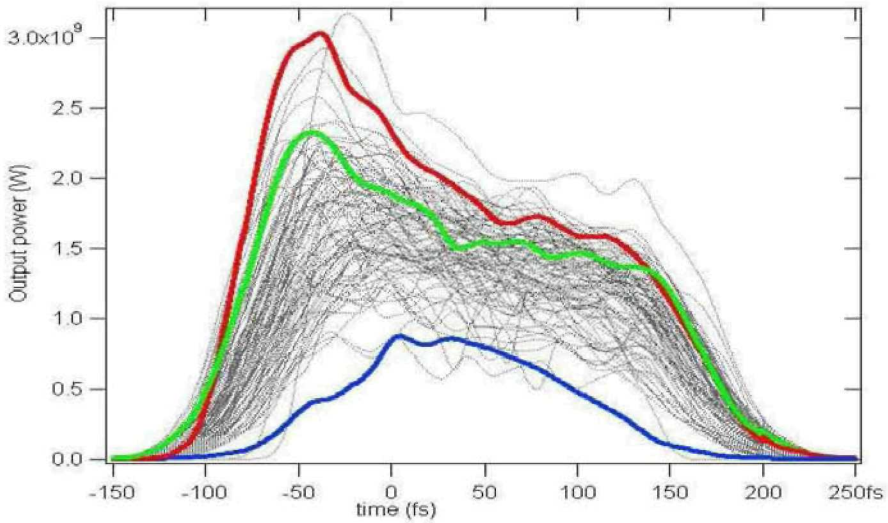


Start to end simulation confirm predictions for jitters

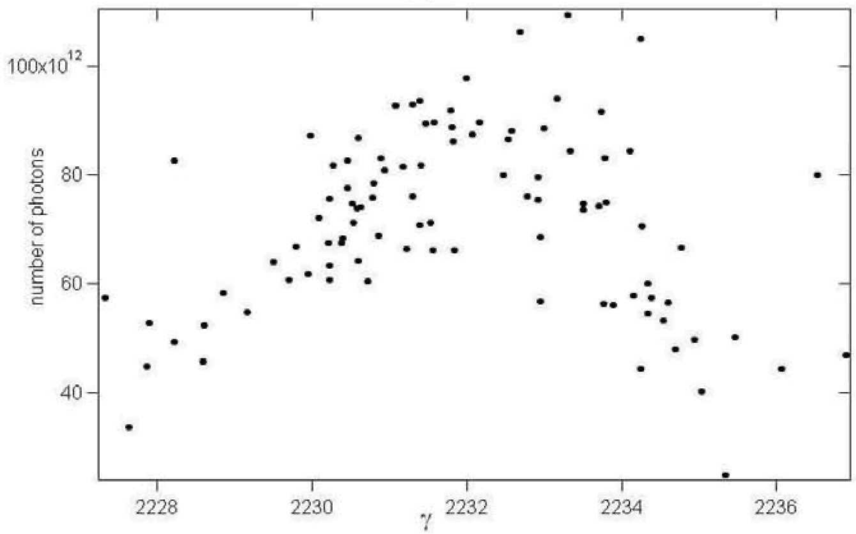
Quantity	Mean Value	Std. Dev.
Gamma	2231.89	0.09%
Current (A)	718	6.6%
Incoherent energy spread	0.32987	19.5%
Normalized emittance	1.35	12.4%

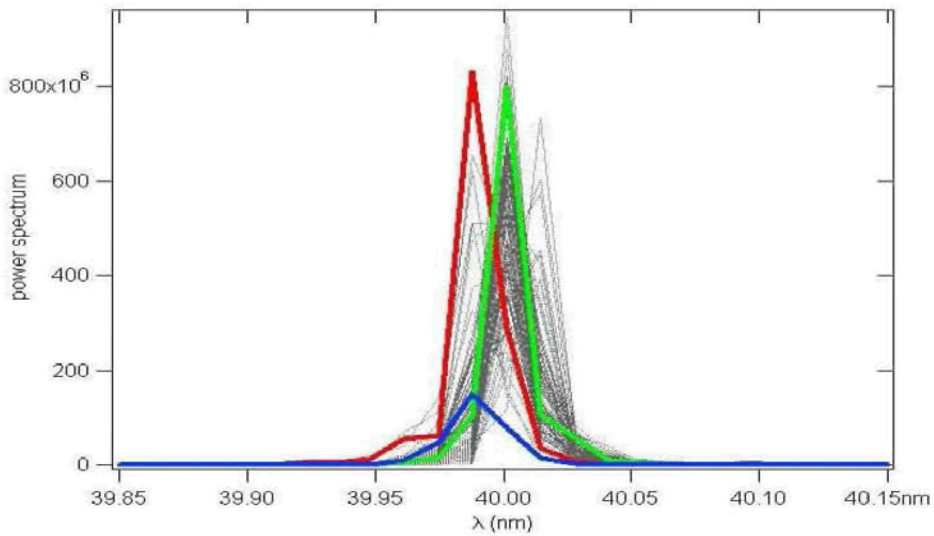
FEL1 results with 100 jittered electron bunches

Results of FEL simulations with the start to end jittered files are in agreement with time independent predictions and confirm the crucial dependence of output power on fluctuations of electron mean energy. On the contrary, the central wavelength shows a very weak dependence on input parameter fluctuations.



Quantity	Mean Value	Std. Dev.
Average pulse width (fs)	73.2	
Average photon number	7.1e+13	**23%**
Average central wavelength (nm)	40.002	0.013%
Average bandwidth	0.033%	
Average Fourier factor	2.2	13%



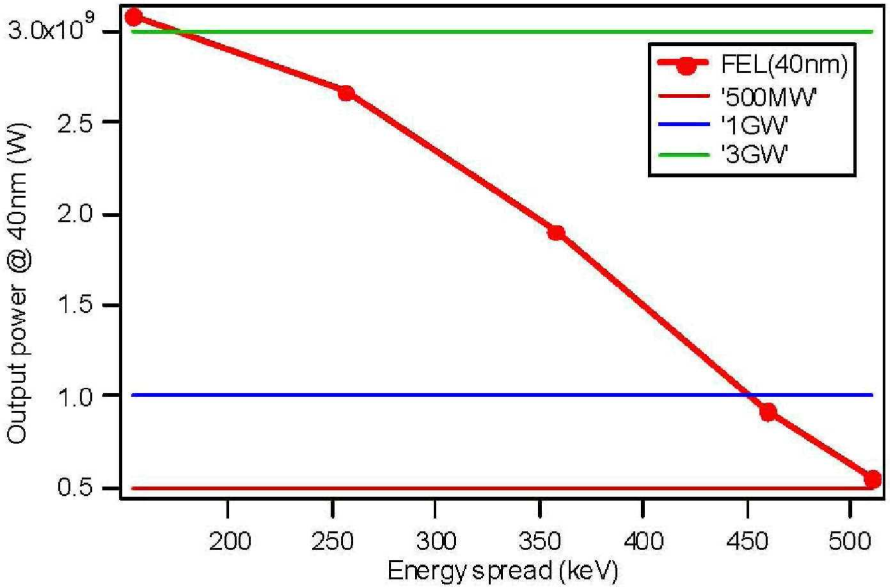


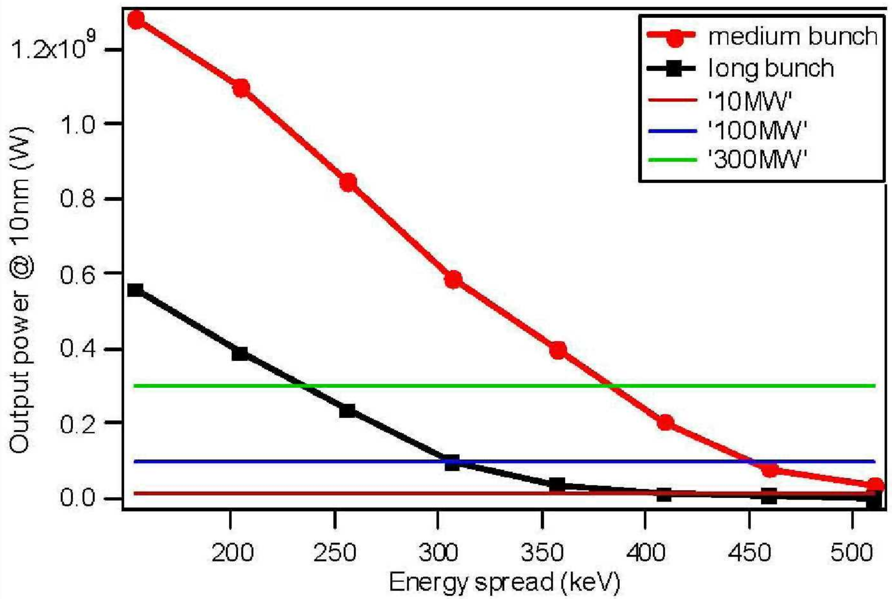
The energy spread problem

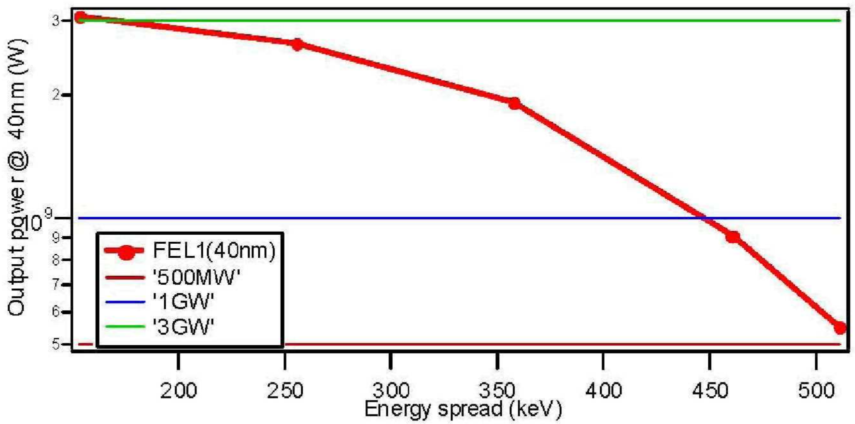
FEL1 and FEL2 have been optimized for electron bunches with an incoherent energy spread of 100-200keV. Larger energy spread can compromise the FEL performance.

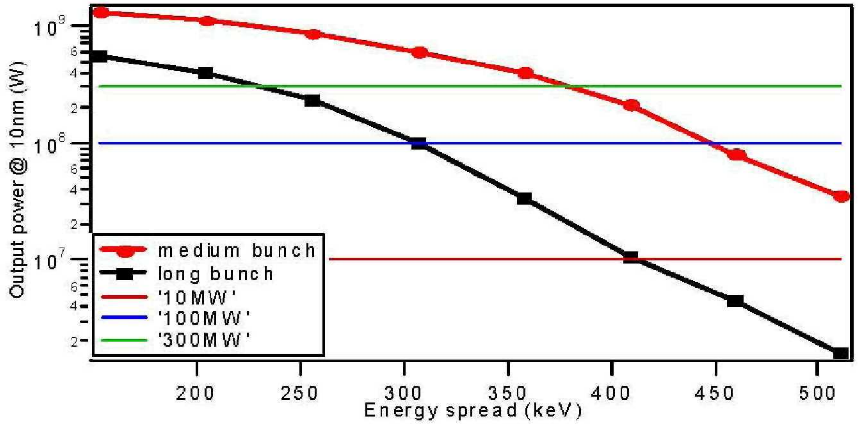
In the case of FEL1 at 40 nm output power larger than 1GW is still possible for $\delta\gamma$ lower than 450keV.

The sensitivity is dramatic in the case of FEL2, that for $\delta\gamma$=300 show only 100MW at 10nm. Performance is better using the medium bunch also for FEL2.





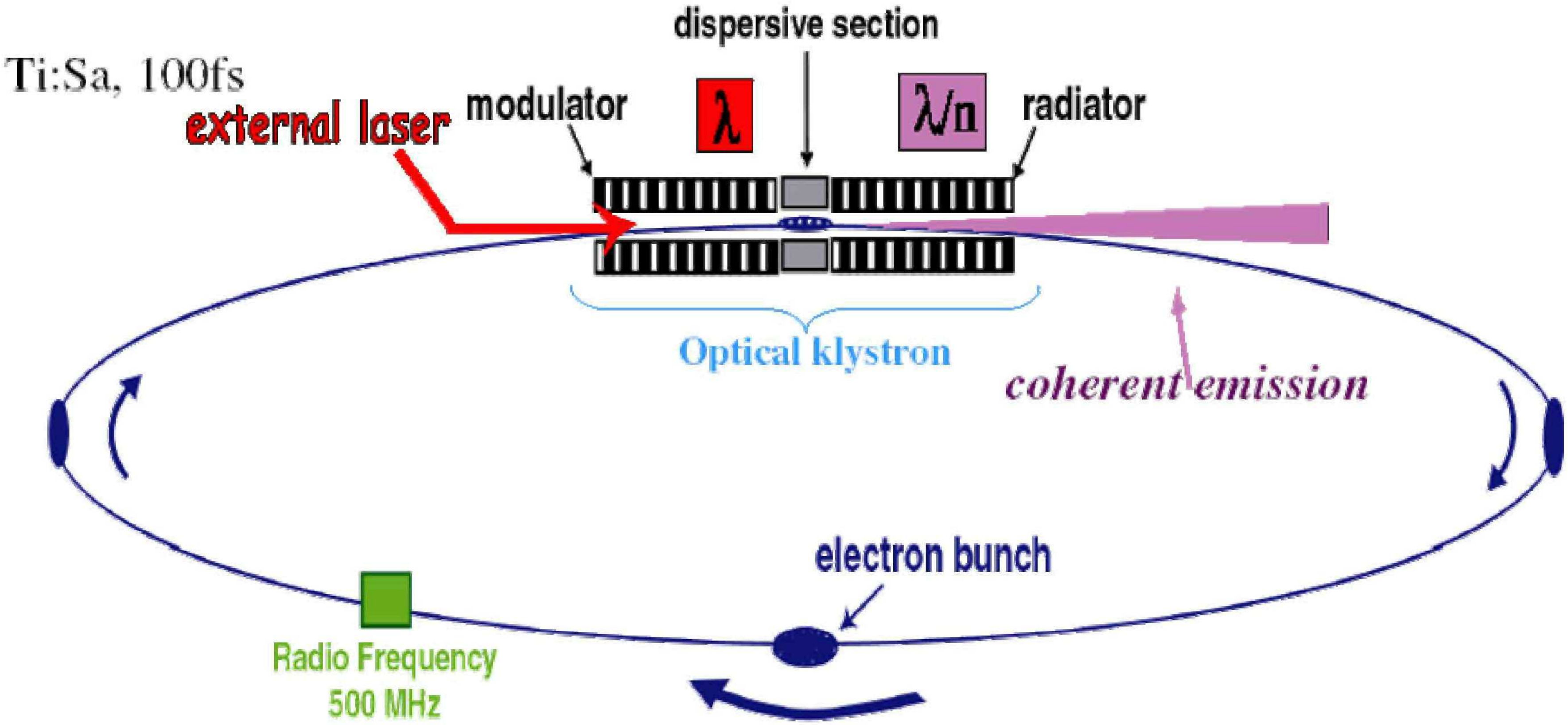




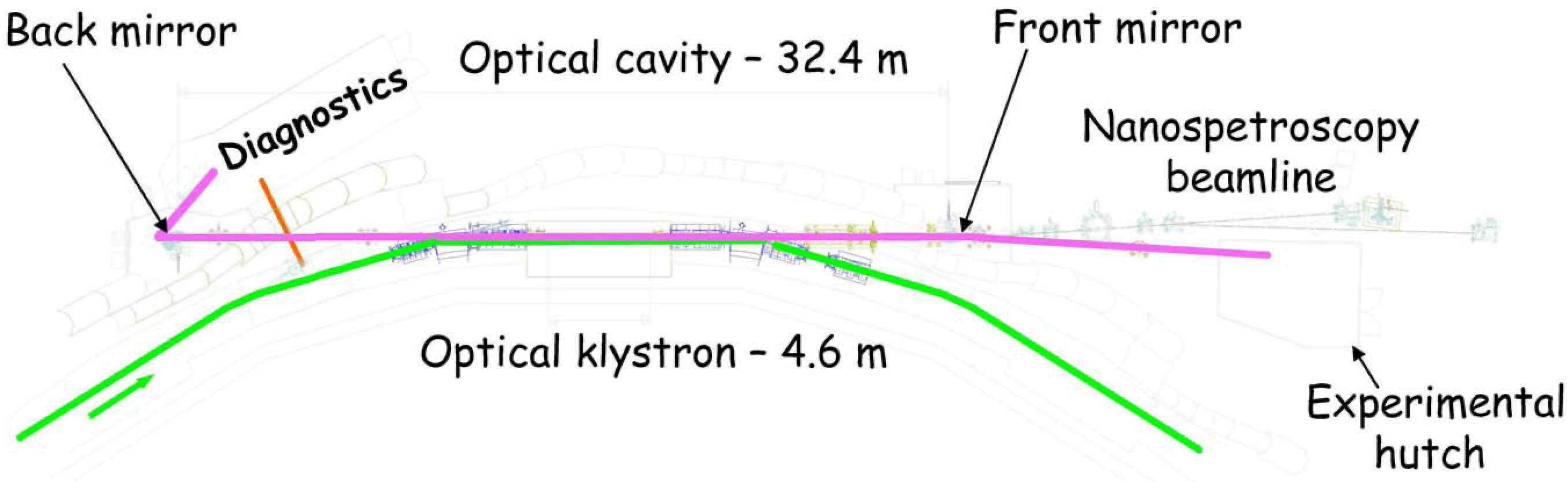
CHG on the Elettra Storage Ring FEL

(on behalf of the SR-FEL group - Sincrotrone Trieste *)*

CHG scheme on a storage ring

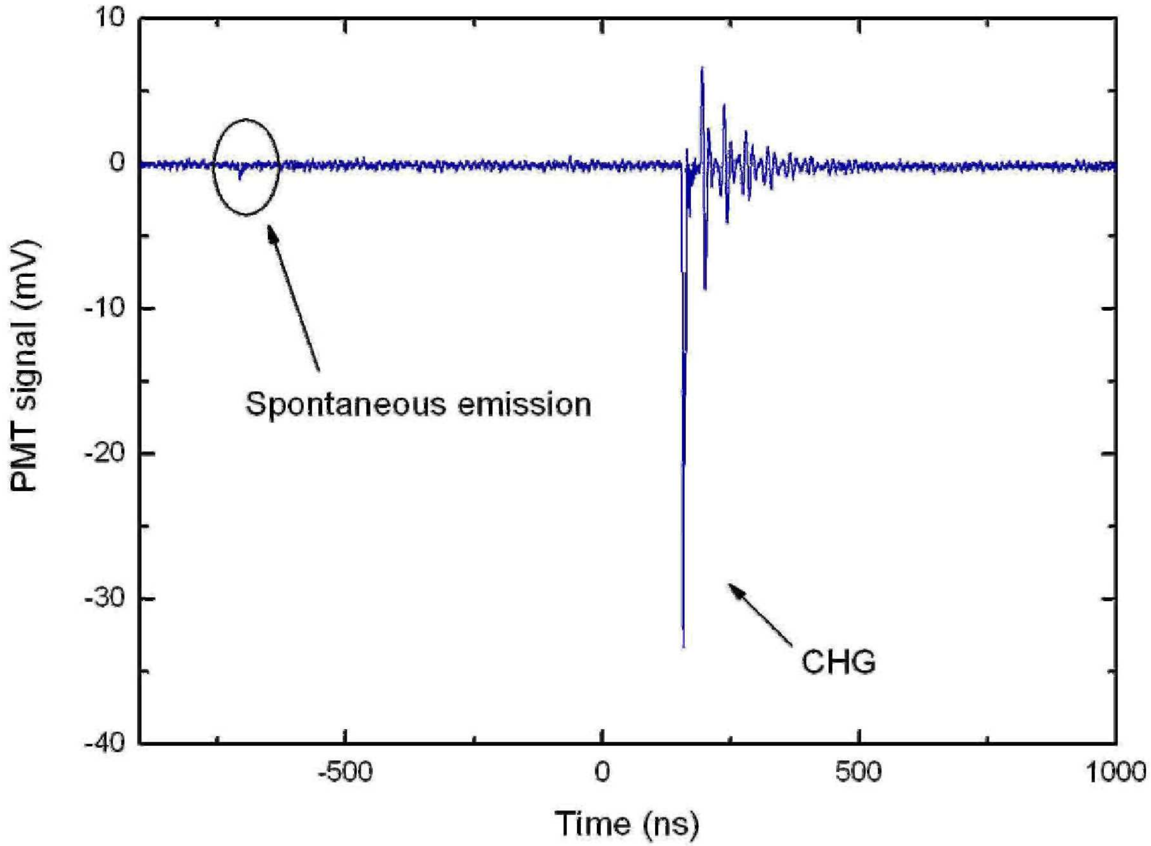


ELETTRA FEL Layout



First CHG evidence on 29 April 2007

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



E_{beam} = 0.75 GeV

I_{beam} = 0.57 mA (single bunch)

Seed:

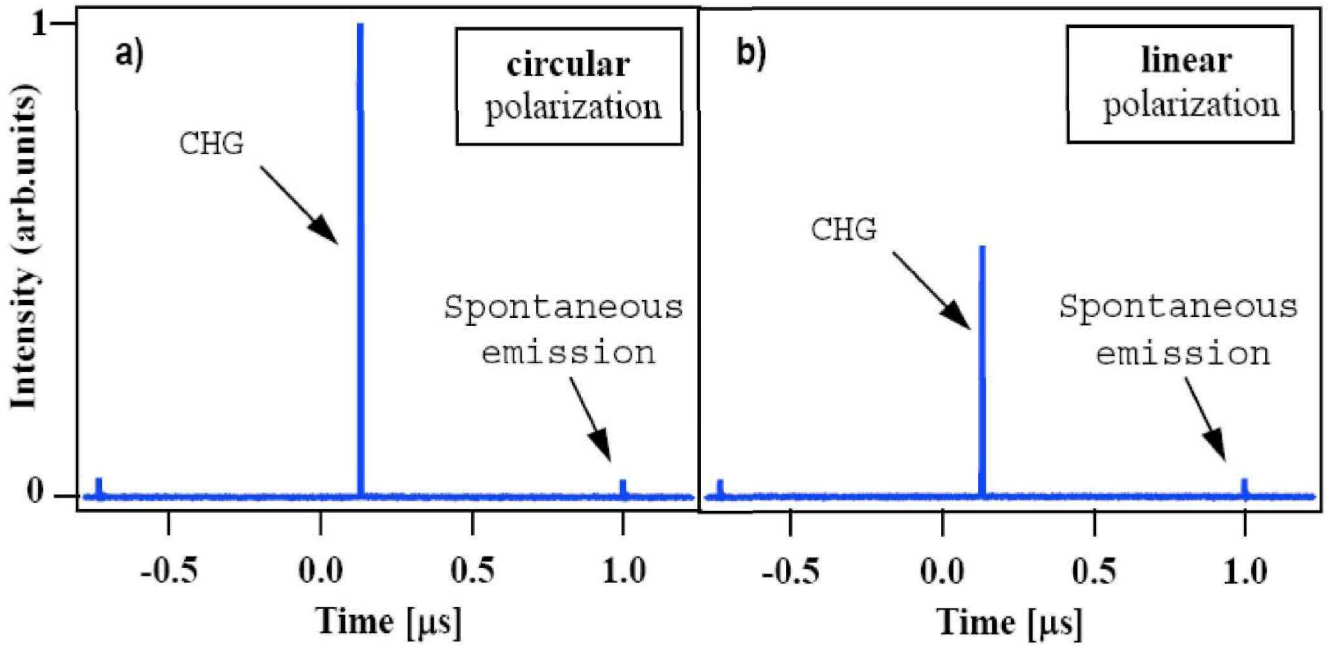
λ = 783 nm

pulse length ≈ 100 fs

pulse energy ≈ 2 mJ

rep. rate = 1KHz

CHG characterization



Considering the difference in the number of photon per pulse and taking into account the difference between the pulse length of synchrotron radiation (~35 ps) and coherent signal (~120 fs), the ratio between peak powers can be estimated to be of the order of 10^4

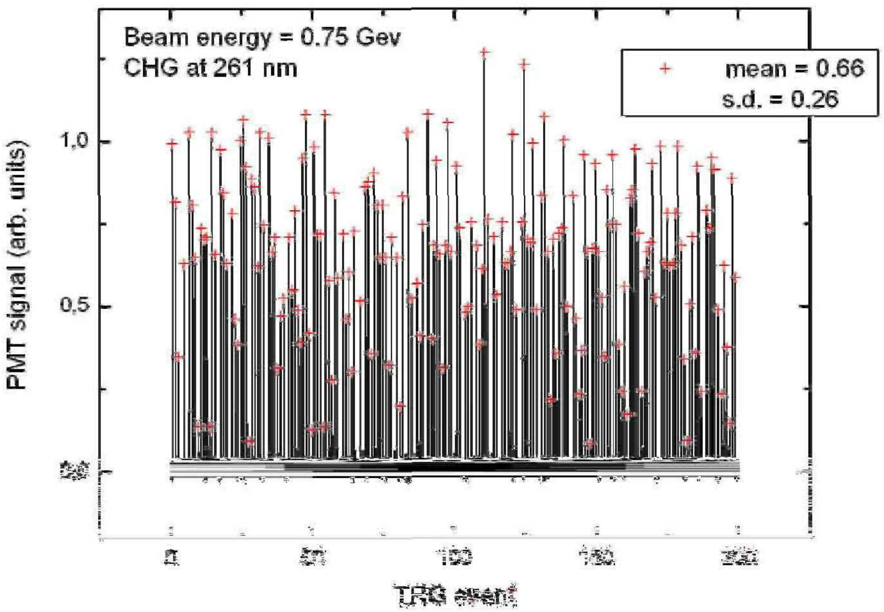
$$(P_{CHG} \simeq 50 \cdot P_{synch} 35ps/120fs = 1.5 \cdot 10^4)$$

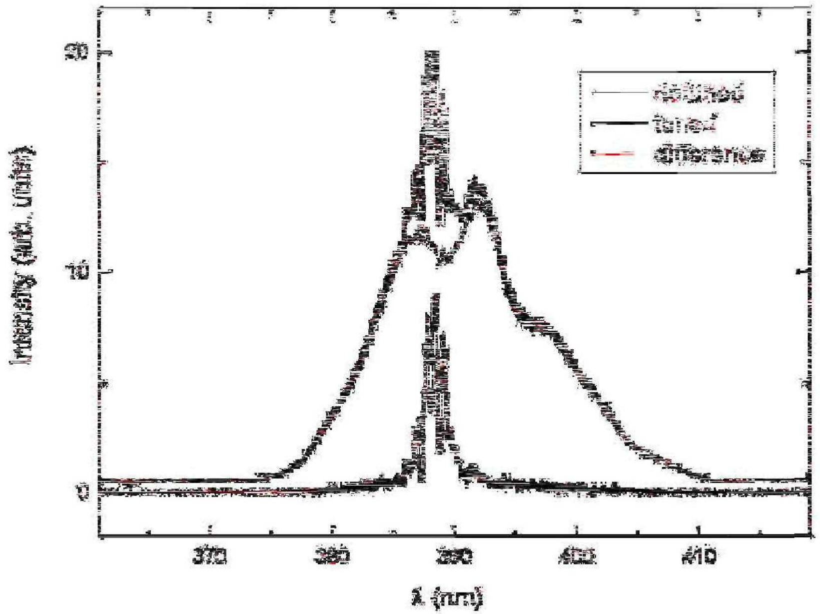
This corresponds to what one can expect from a qualitative calculation using the parameter of our setup

$$P_{CHG} \propto N_{coh}^2 \qquad N_{coh} \simeq B \cdot I \cdot \Delta T_{las}/Q$$

$$P_{synch} \propto N_{bun} \qquad N_{bun} \simeq I \cdot \Delta T_{bun}/Q$$

Seed 780nm → CHG 390nm (2nd) & 260nm (3rd)

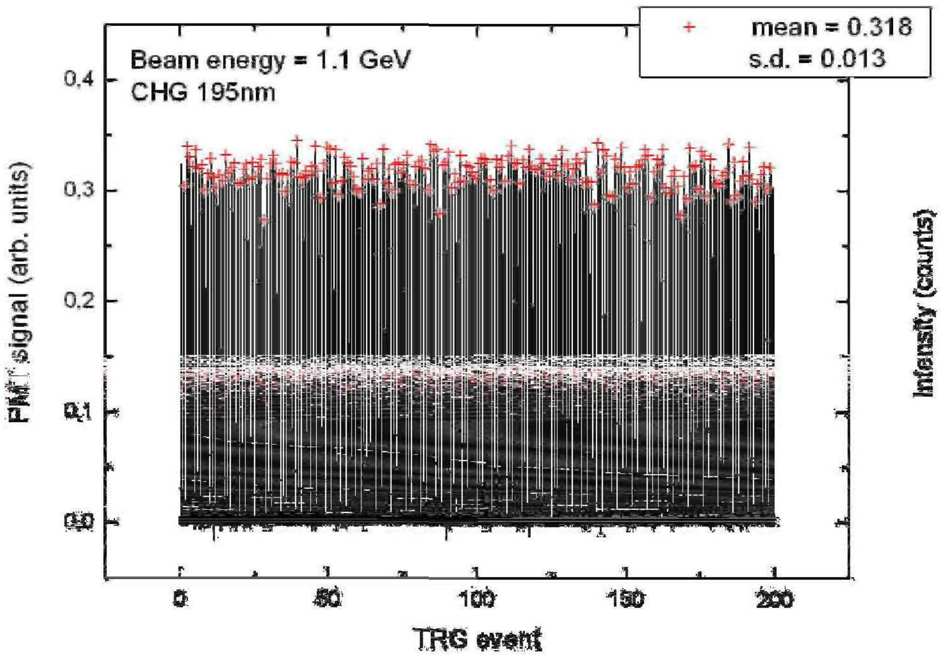


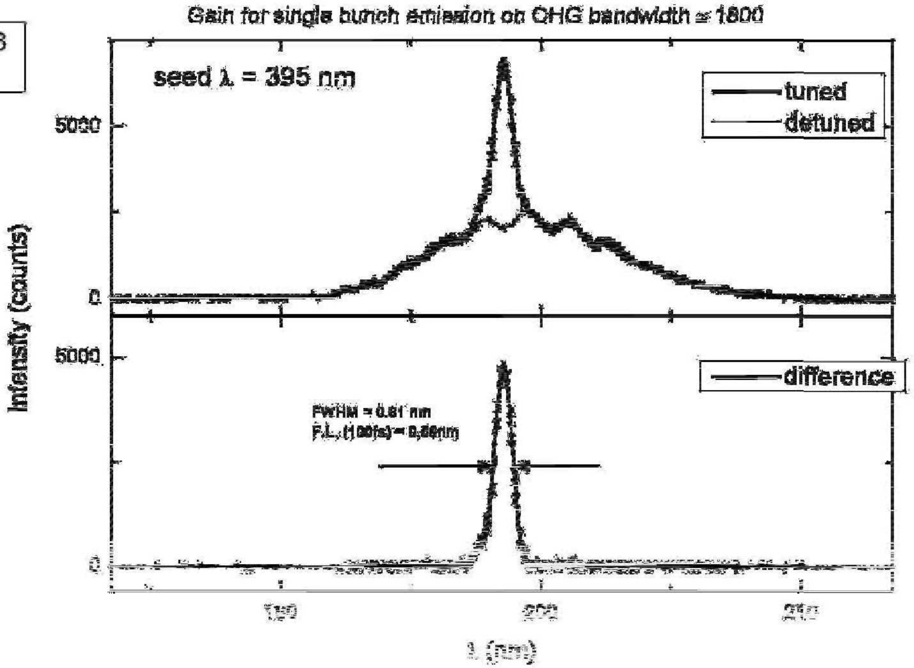


Beam instability at 0.75 GeV and timing jitter/drifts
prevent the optimization of the experimental parameters

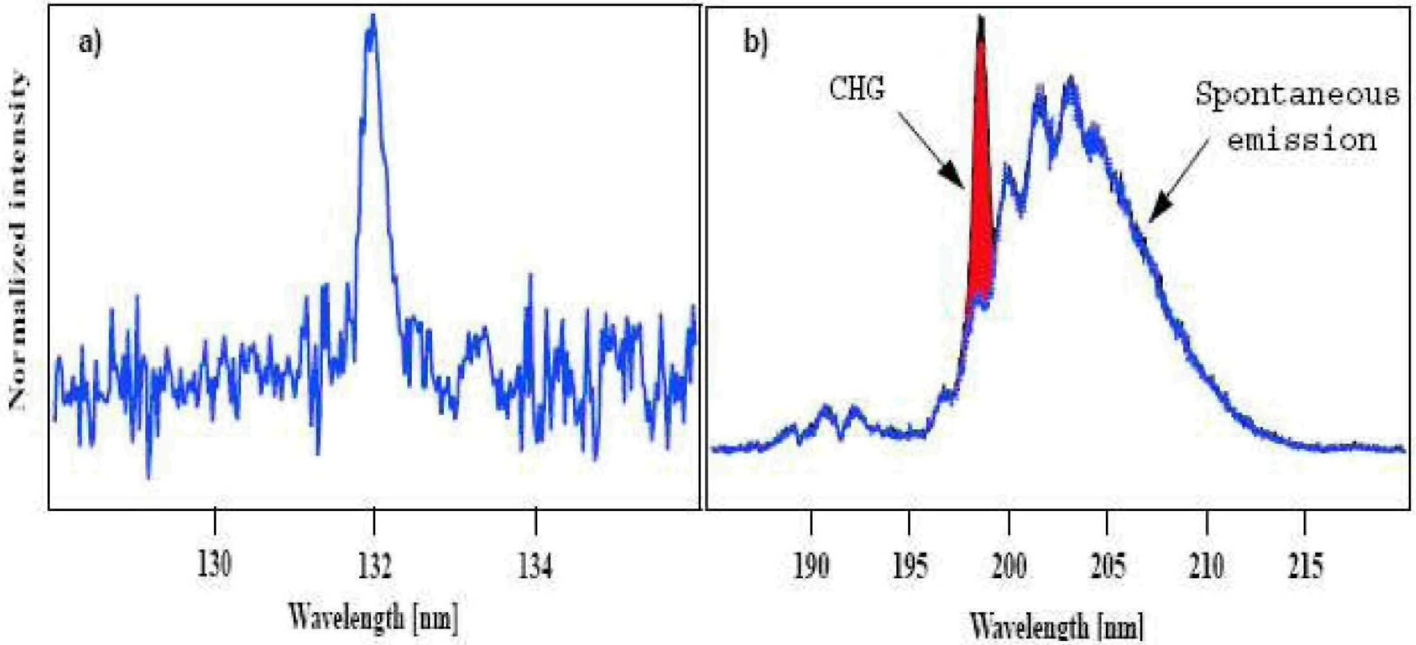
Seed at 390nm ➔ E_{beam} = 1.1 Gev

- better stability
- from spectra we can estimate CHG gain with respect to spontaneous emission



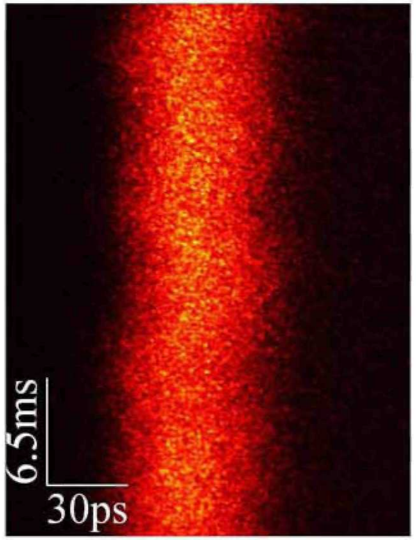


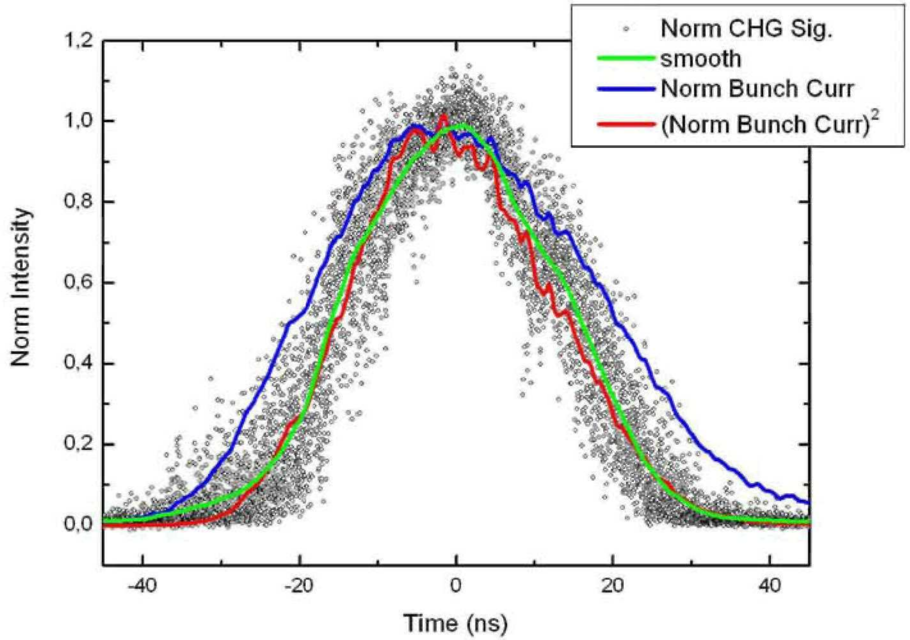
Spectral stability

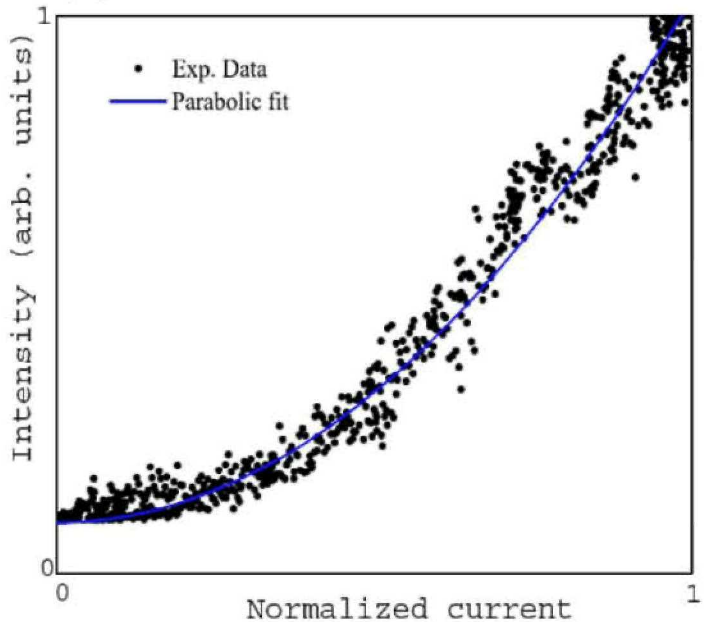


a): Spectrum of the coherent emission at 132 nm (linear polarization). The integration time is 1 ms; the spectrum is obtained after subtraction of the background due to spontaneous emission. b): Spectrum of spontaneous and coherent emission for the case in which the radiator is tuned at 203 nm, i.e., slightly mismatched with respect to the second harmonic of the seed laser (198.5 nm).

Quadratic dependence of CHG on bunch current





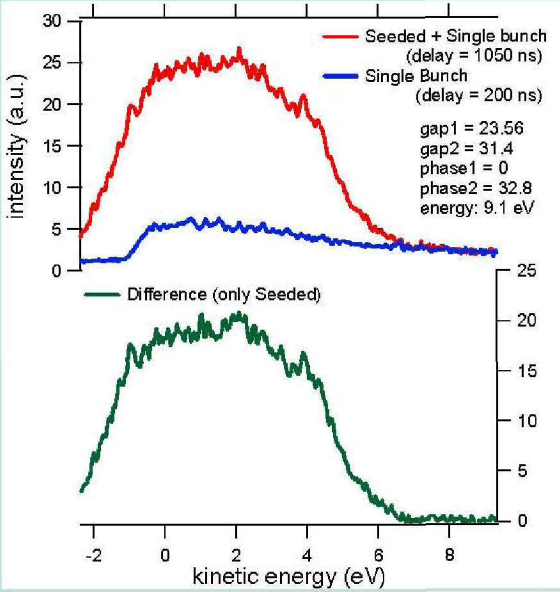


Quadratic dependence of the coherent harmonic at 132 nm vs. (normalized) bunch current. Dots represent experimental data; the curve is a t obtained using a quadratic function.

Test experiments

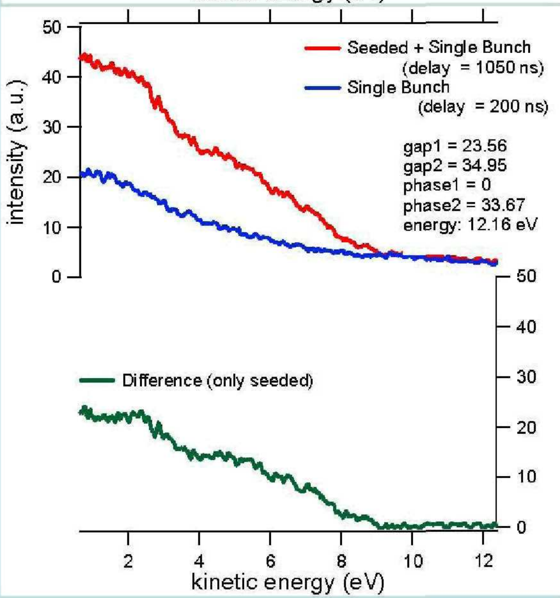
- Nanospectroscopy (Elettra):
  - PEEM with gated detector
- CESYRA (CIMAINA/UniMi)
  - TOF (mass spectrometry)

Nanospectroscopy



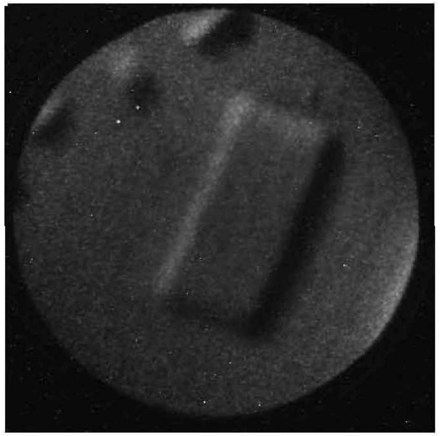
VB UPS on Ag/W(110)

3^{rd} harmonic
λ = 133 nm

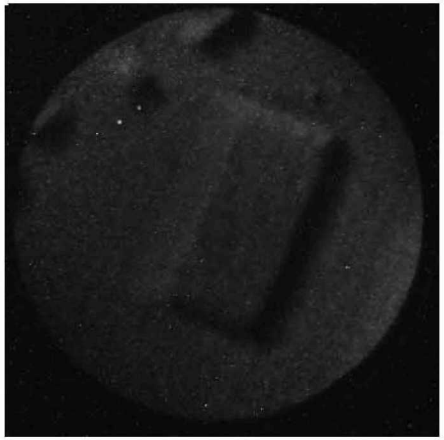


4^{th} harmonic
λ = 99.5 nm

Imaging on SiO_2 patterned sample

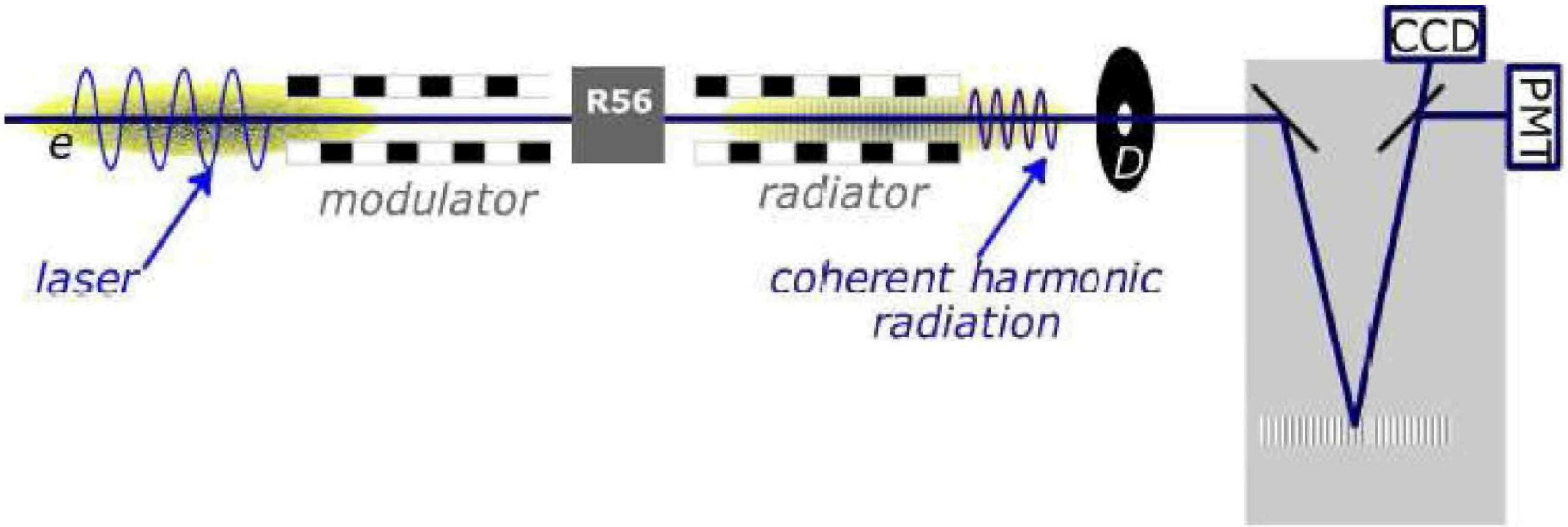


seeded



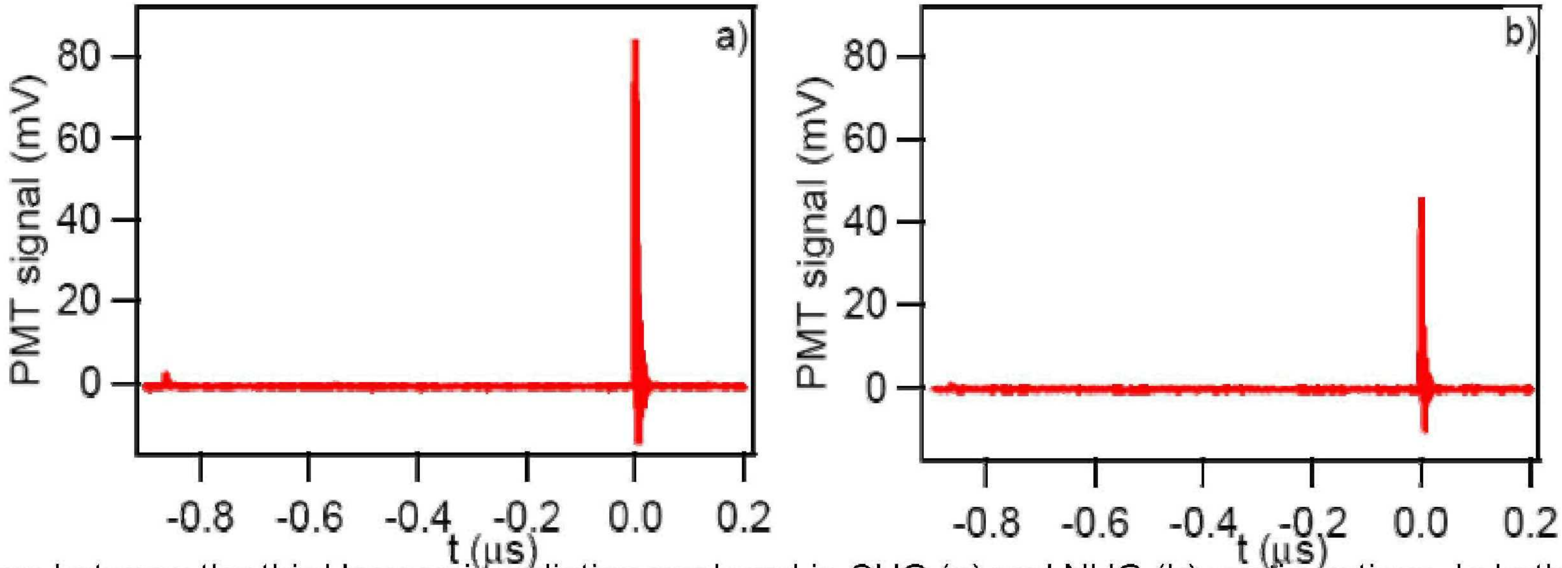
spontaneous emission

Comparison between CHG and NHG



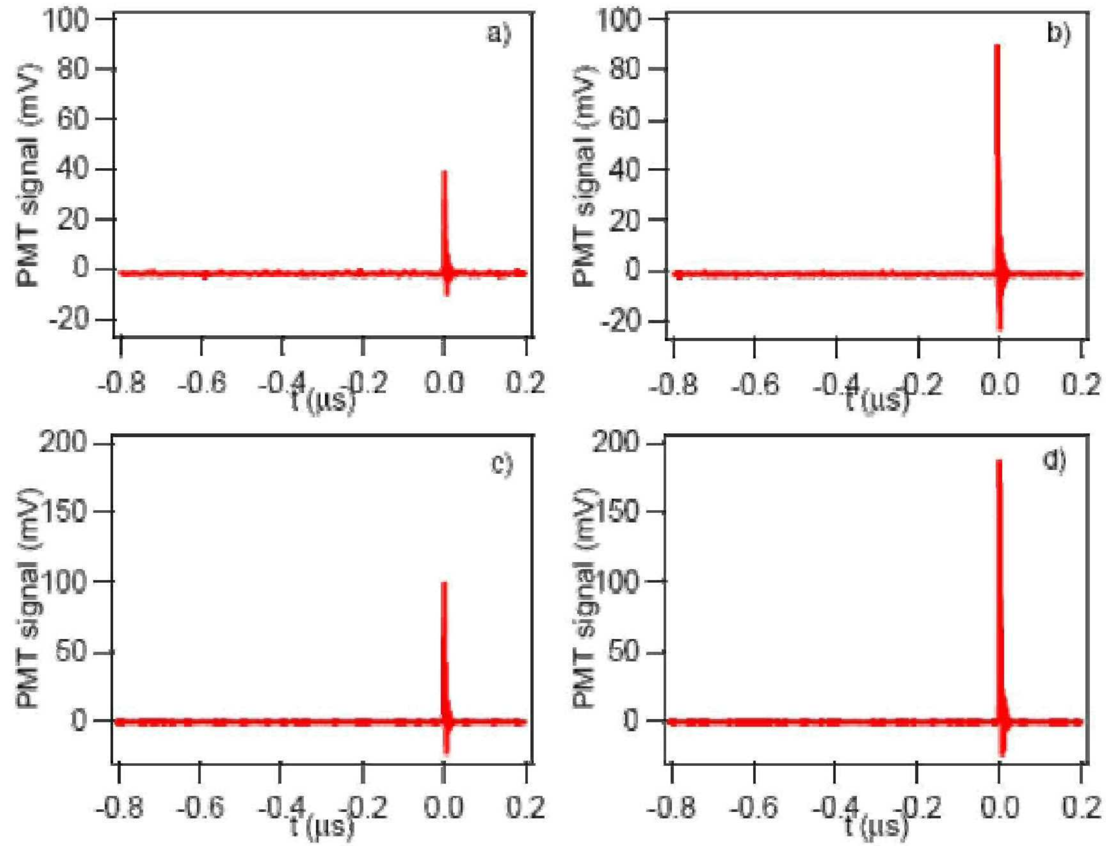
- Sketch of the experimental setup used for the investigation of harmonic generation in a FEL. A powerful Ti:Saphire laser interacts with the electron bunch (e) within the modulator and induces a modulation of the electrons' energy. After the conversion of the energy modulation into spatial bunching, which occur into the magnetic chicane (R56), the bunch enters the radiator and start emitting coherently at the resonant wavelength and, eventually, at its harmonics. The produced coherent harmonic radiation passes through a diaphragm (D) and is transported into a diagnostic area, where temporal (PMT) and spectral (CCD) analyses are performed. The position of the diaphragm de nes the angle of emission with respect to the undulator's axis considered for the measurement.

CHG and NHG



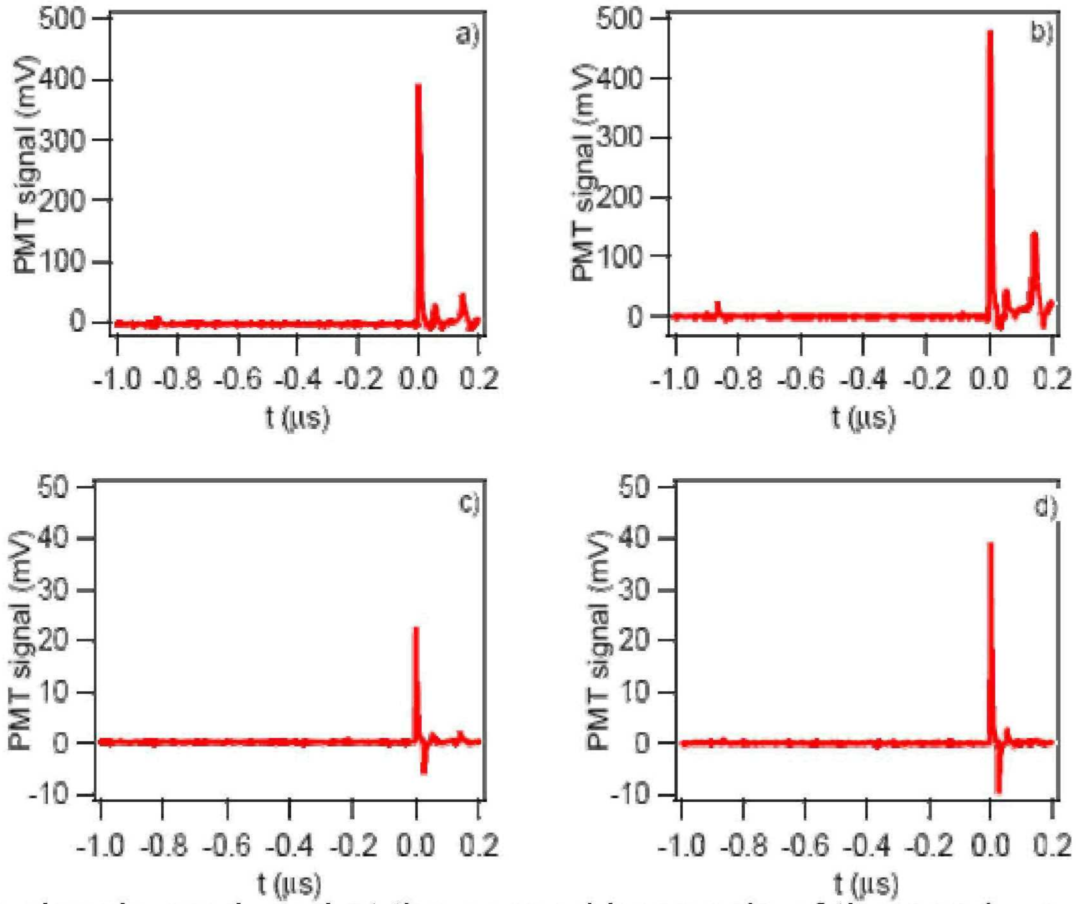
Comparison between the third harmonic radiation produced in CHG (a) and NHG (b) configurations. In both cases the modulator and the seed laser are in horizontal polarization. The radiator is tuned to the third harmonic in horizontal polarization (a) and to the fundamental in horizontal polarization (b).

CHG and NHG



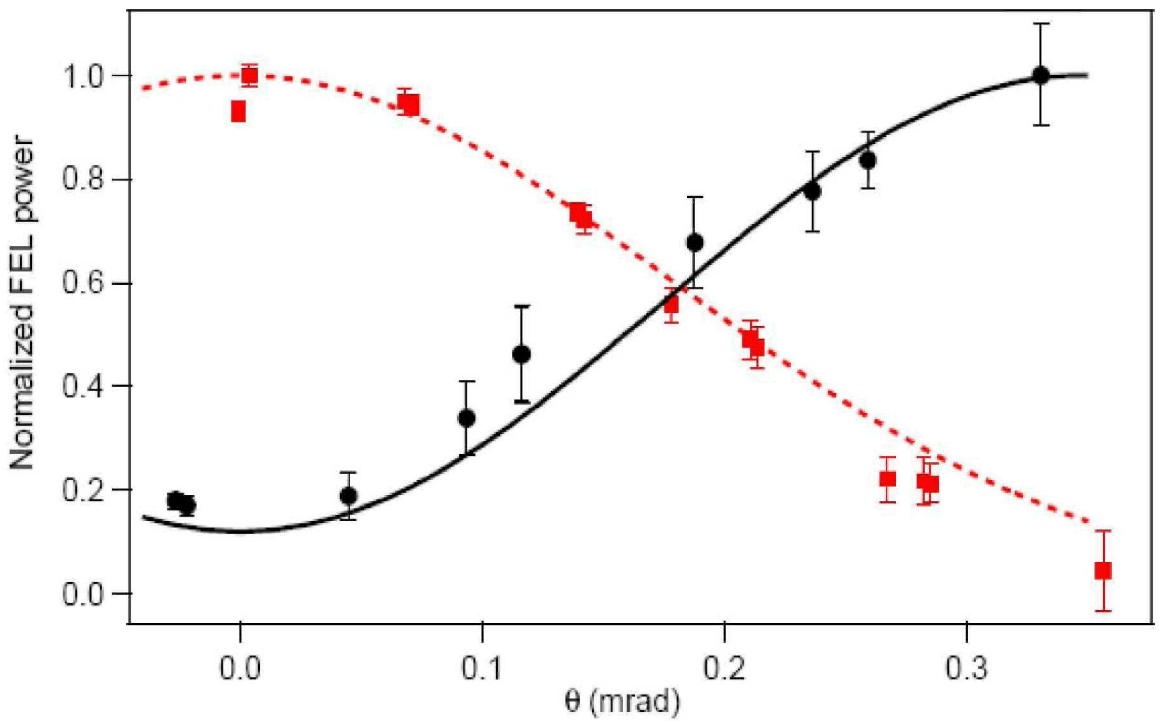
- Comparison of the harmonic radiation produced in CHG configuration at the second (a,b) and third (c,d) harmonics of the seed wavelength. The radiator is set in horizontal (a,c) or in circular (b,d) polarization, while the modulator and the seed are in horizontal polarization.

CHG and NHG



- Coherent harmonic signals produced at the second harmonic of the seed wavelength in CHG (a,b) and NHG (c,d) configurations. Figures (a,c) refer to a condition where the seed laser, the modulator and the radiator are in planar polarization, while Figs.(b,d) refer to a condition where both the seed and all undulators are set in circular polarization. Data reported in Figs.(a) and (c) refer to the same experimental conditions, and can be used for a relative comparison. The same holds for Figs.(b) and(d).

CHG and NHG



- Measured angular distribution of the second harmonic in the case of CHG (squares) and NHG (dots) with helical undulators. Measurements are well fitted by theoretical curves,which have been obtained by integrating the expected Gaussian profile (dashed line, CHG case) and the profile predicted in [9] (continuous line, NHG case), over an angle of 0.09 mrad.

Perspectives for SR-CHG

- Seed with Ti:Sa 3rd harmonic (260nm)
- CHG down to 87nm (14.3 eV)
- Pump and probe beamline for time resolved experiments
- Compatibility with normal operation mode at 2.0 GeV (non symmetric SR filling)

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