Last year progress in laser pulse shaping at INFN-Milano

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Introduction

Title of Milano - JRA2 - CARE scientific task:

Investigate and test systems for complicated ultra-fast optical waveforms according to user specifications, as those for the new generation of FEL, with benefits for linac photo-injectors.

Two technologies

- LCM-SLM (liquid crystal mask – spatial light modulator)
- Dazzler-AOPDF (acousto optic programmable dispersive filter)

Introduction

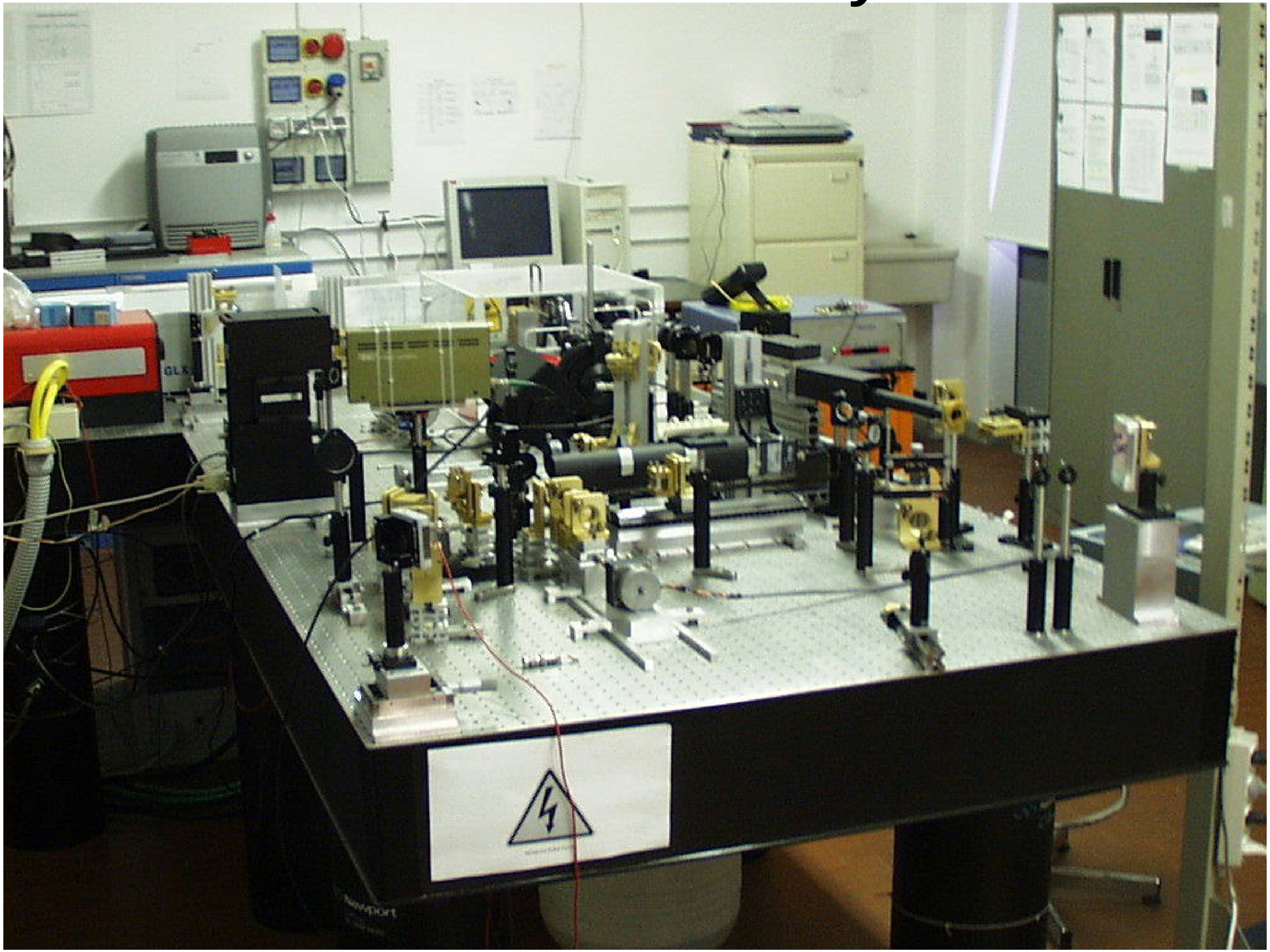
Since the last meeting

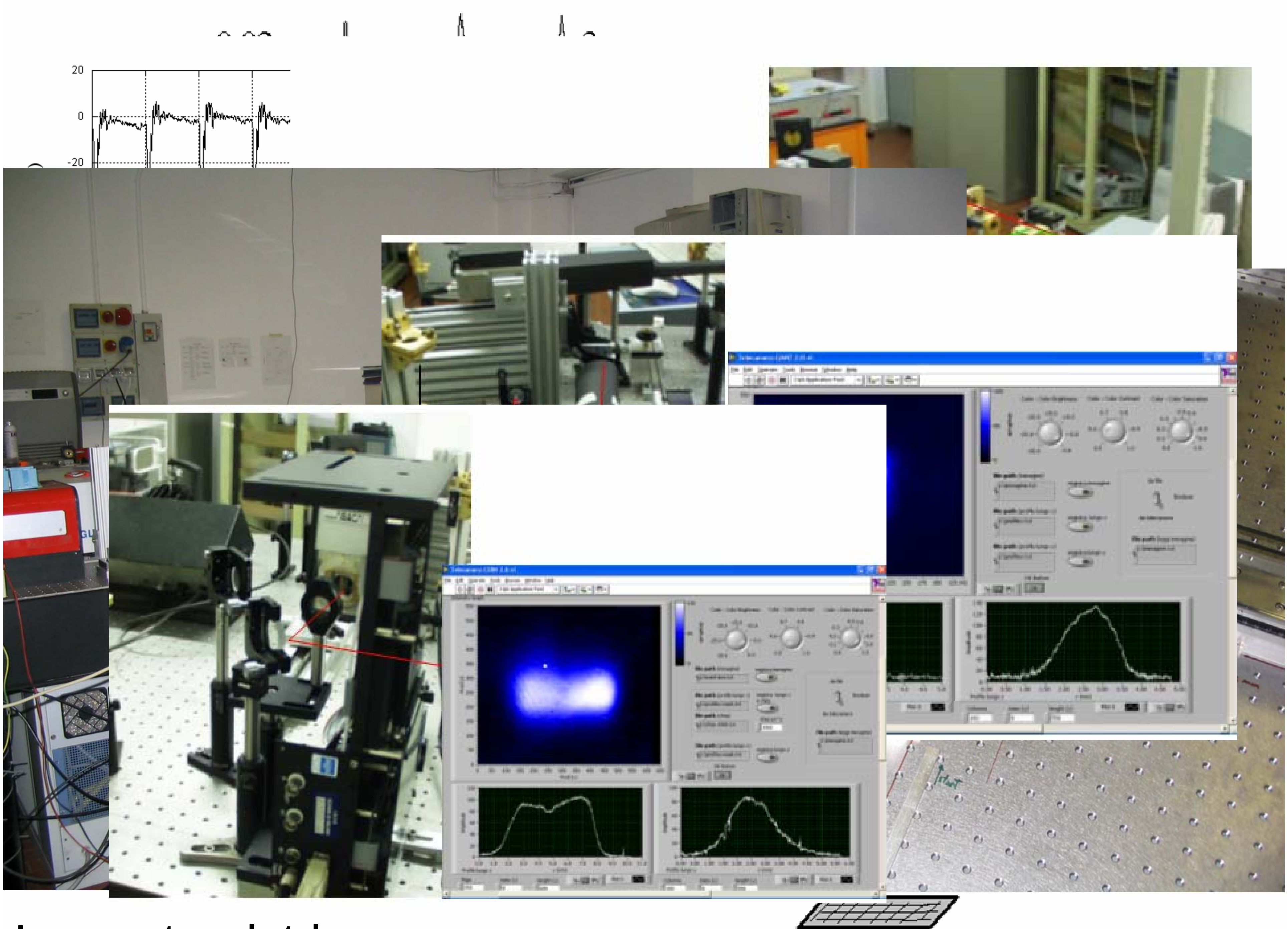
- We built a laser system in Milano for the generation of target pulse waveforms
  - Nd-YAG laser souce
  - Diagnostic tools
  - Feedback loop with LCM-SLM to obtain automatically the target pulse waveforms

- Physics and relevant simulation program of pulse temporal profile modulation in 2° and 3° harmonic generation
  - Positive experimental test in SPARC-frascati lab. of the theoretical work

The Milano laser system

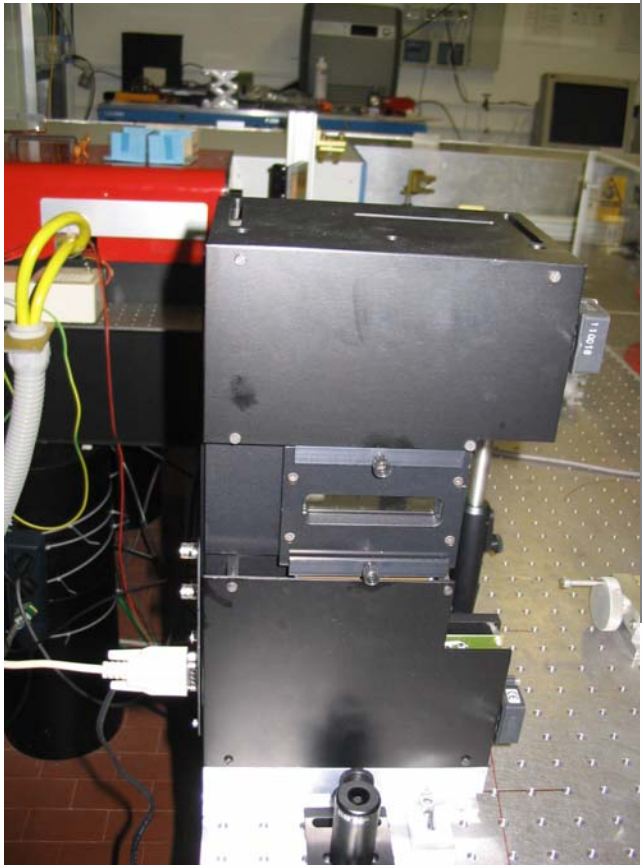
The Milano laser system

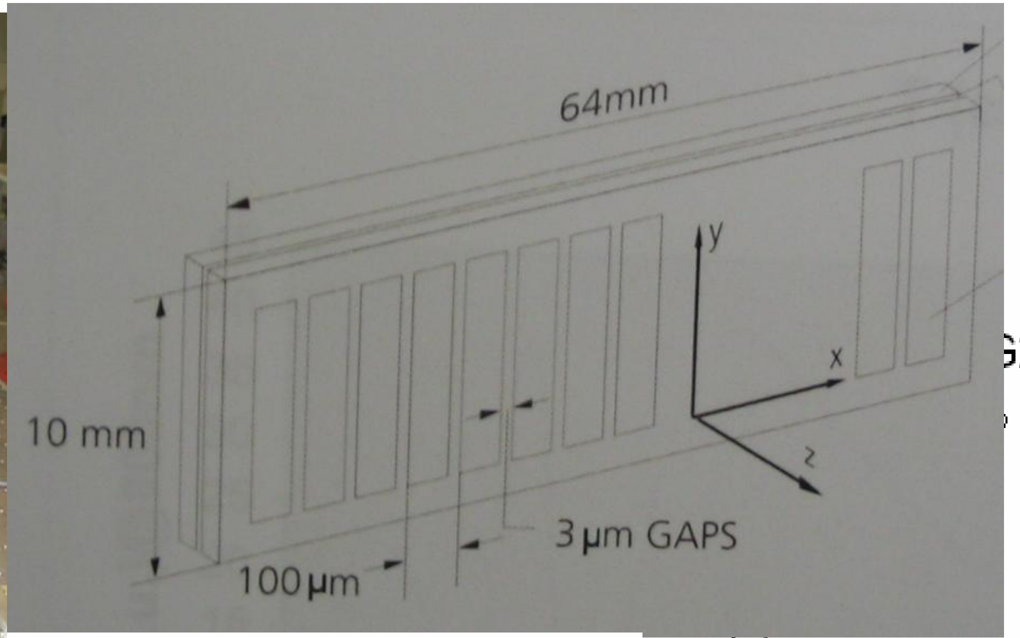




Laser system sketch

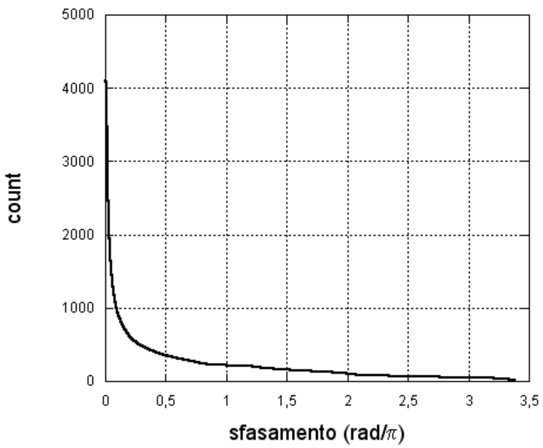
4F-system





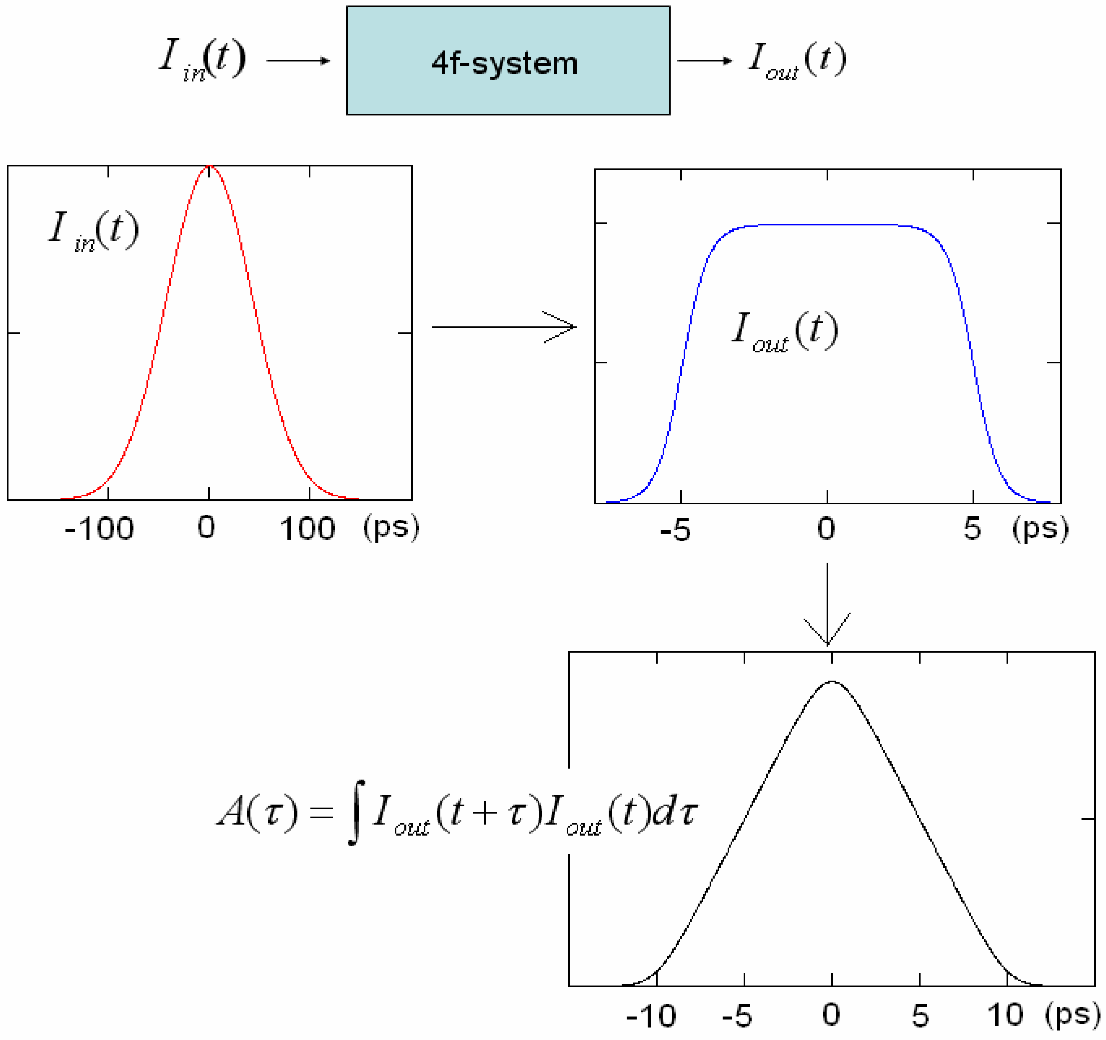
G2

orrelator



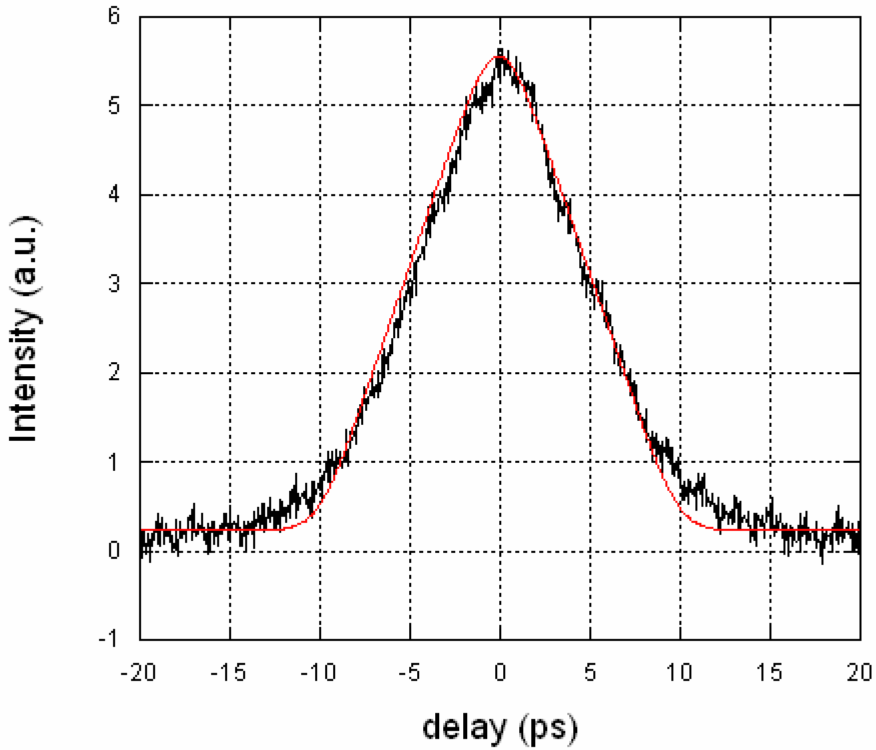
$$w_0 = \frac{\lambda_0 f}{\pi \cdot w} \frac{\cos(\theta_i)}{\cos(\theta_d)}$$

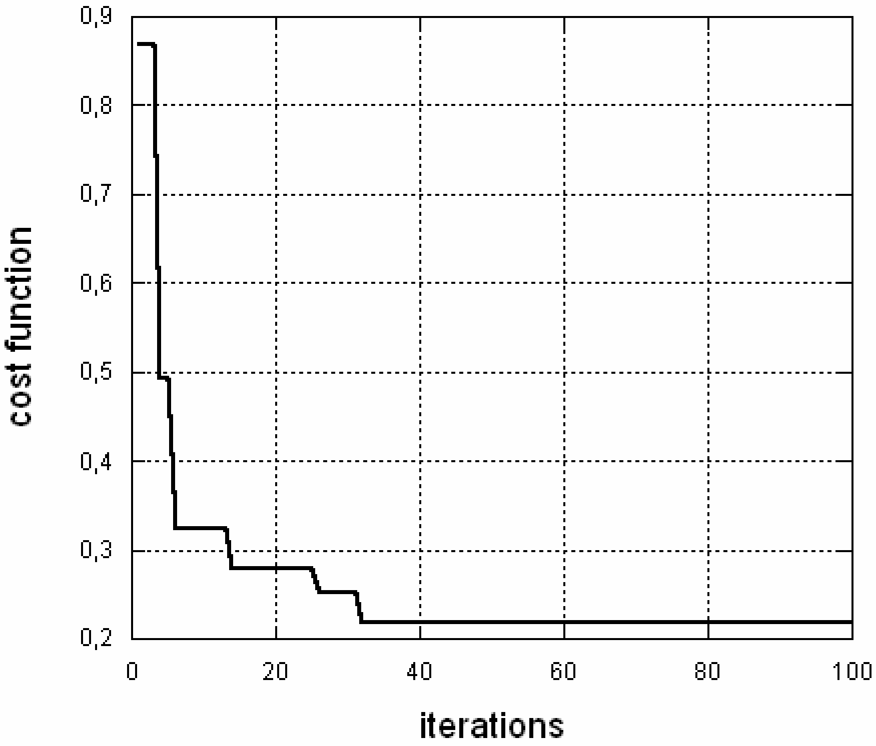
Feedback



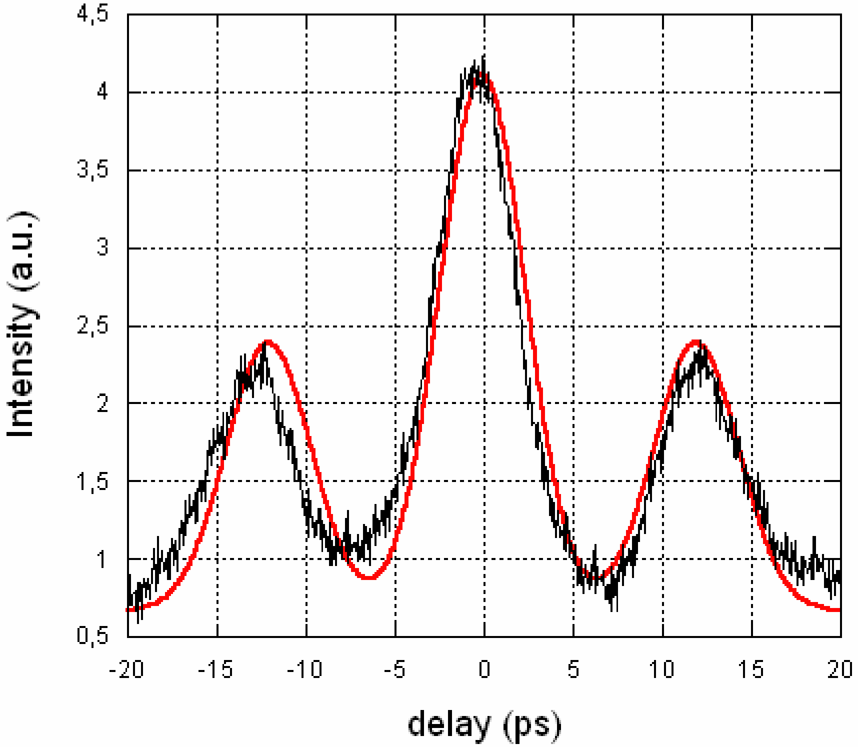
$I_{in}(t)$
4f-system
$I_{out}(t)$
$I_{in}(t)$
-100
0
100
(ps)
$I_{out}(t)$
-5
0
5
(ps)
$A(\tau) = \int I_{out}(t+\tau) I_{out}(t) d\tau$
-10
-5
0
5
10
(ps)

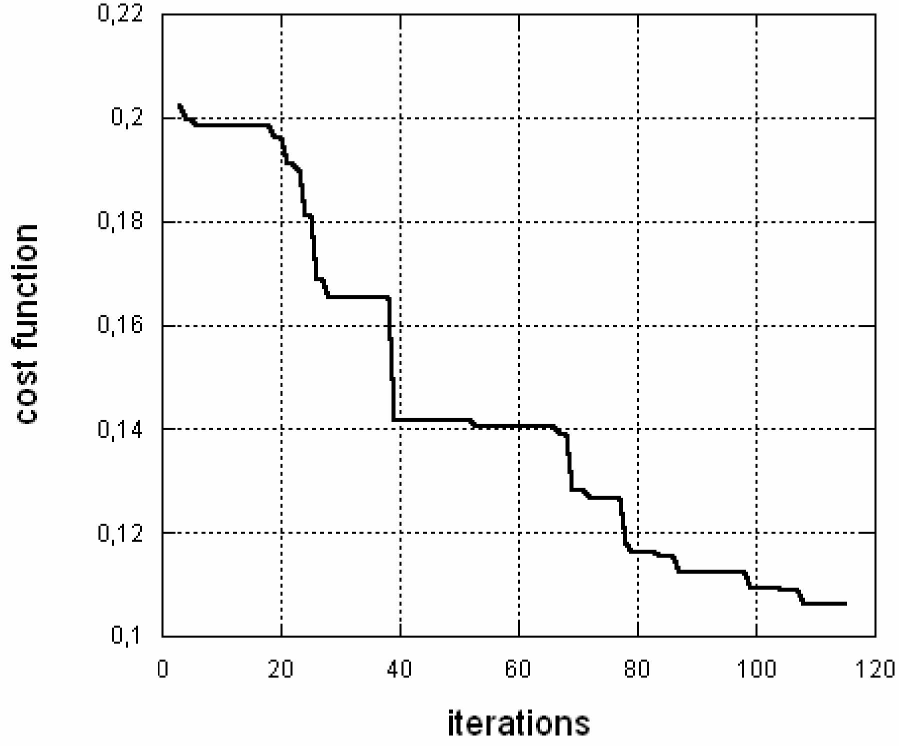
Square pulse





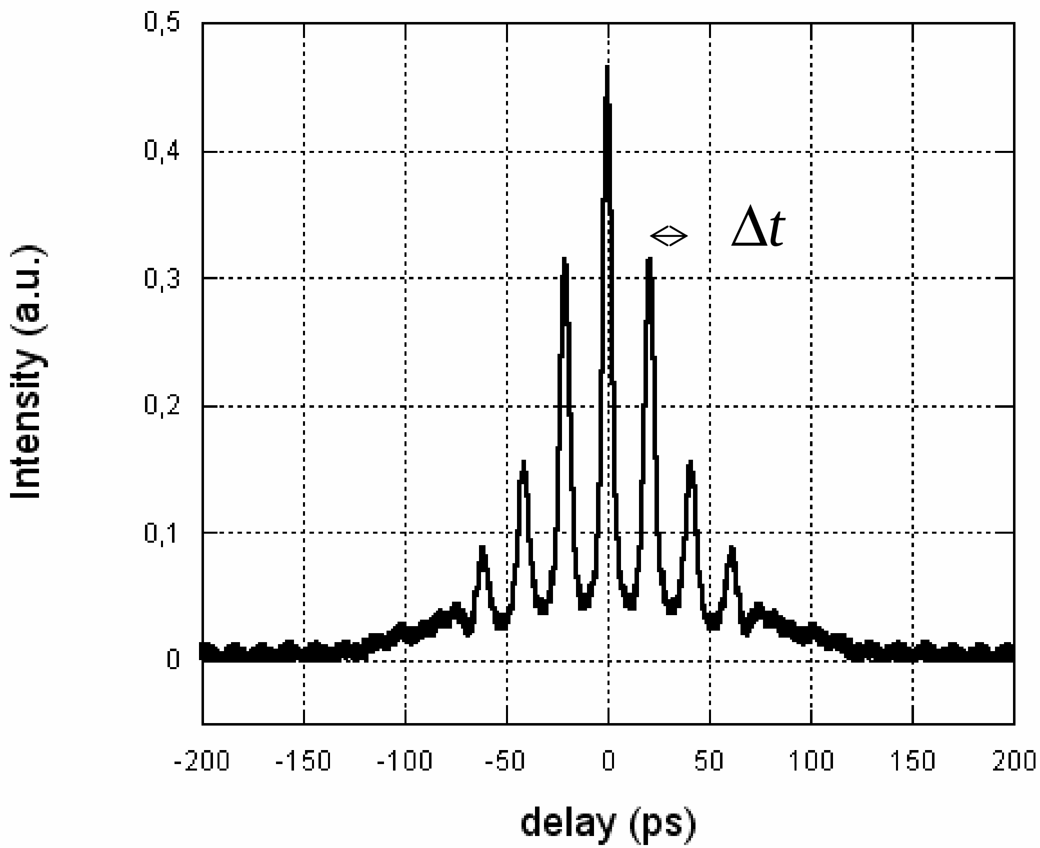
Two pulses

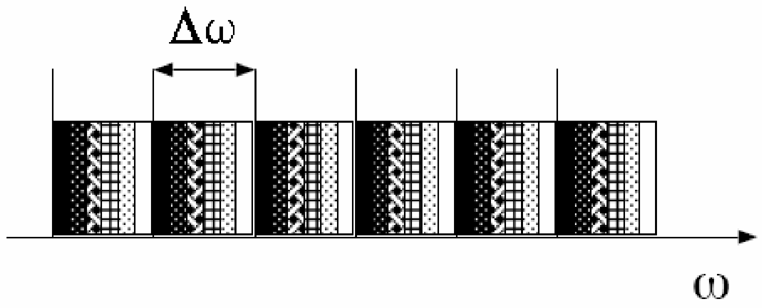




$$\Phi_{RND} = \frac{1}{2}\alpha_{RND}\omega^2 + RND(\omega)$$

Pulse train

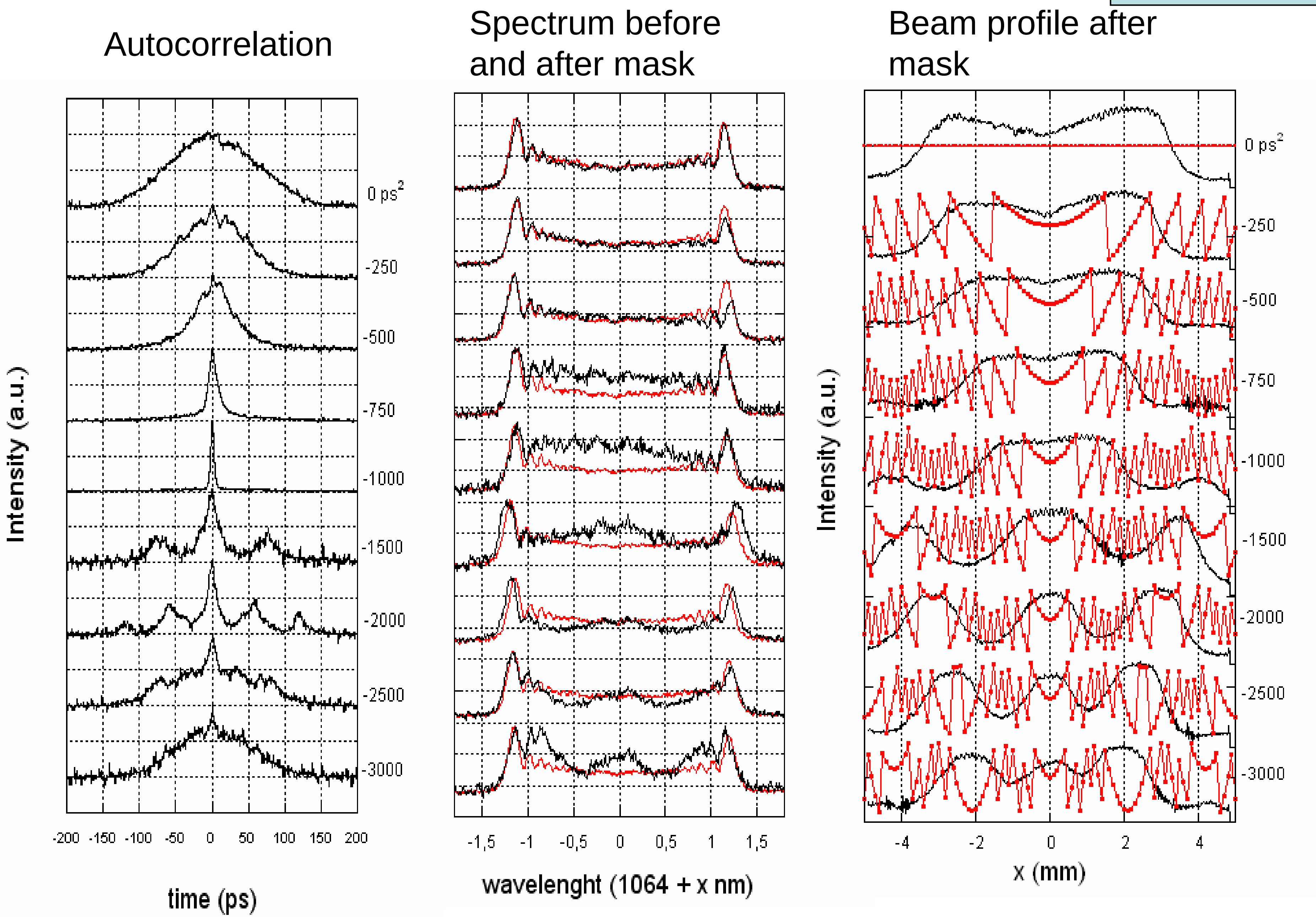




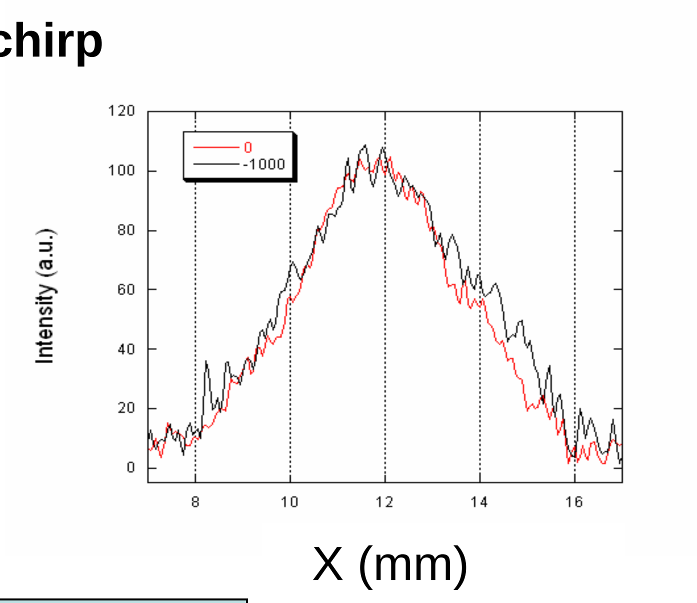
$$\Delta t = \frac{2\pi}{\Delta\omega}$$

Autocorrelation – spectrum – beam profile after mask vs chirp

$$\Phi(\omega) = \frac{1}{2}\alpha\omega^2$$



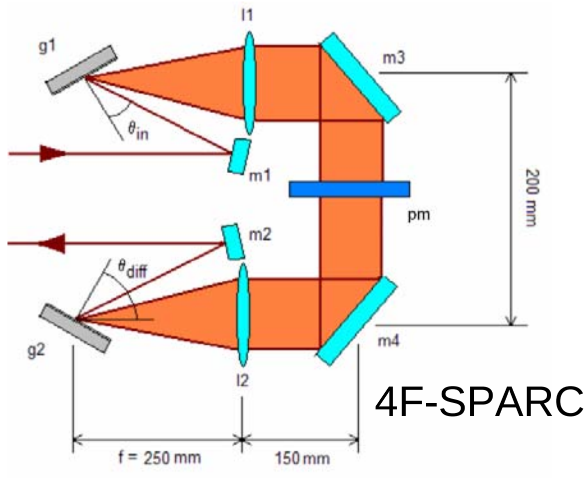
Beam profile (far field) vs chirp



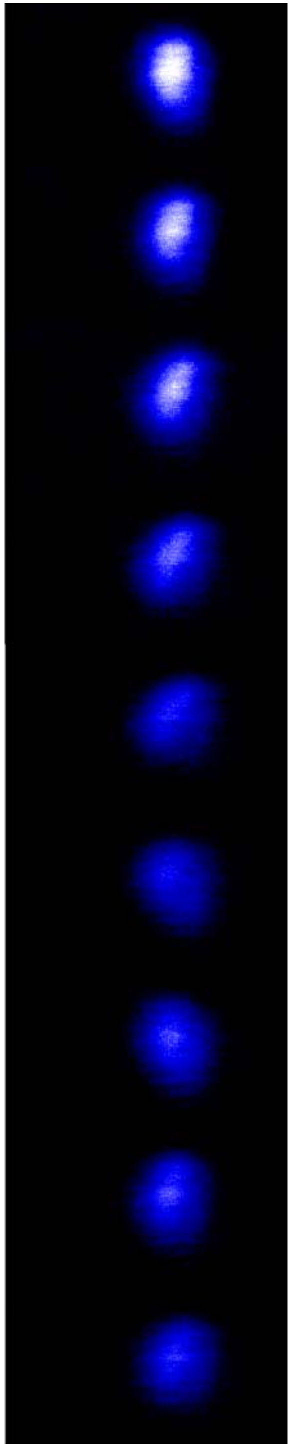
$$\Delta\tau \cdot \Delta\omega_{pixel} \leq \frac{2}{3}\pi$$

$$\Delta\tau_{\max-sparc} \approx 10ps$$

$$\Delta\tau_{\max-sfera} \approx 30ps$$



4F-SPARC



Pulse shaping with harmonics

- We have developed the theory of pulse shaping within non-linear crystals for the hamonics generation: "Rectangular pulse formation in a laser harmonic generation", S.Cialdi, F. Castelli, I. Boscolo, Report INFN-BE-05-1 (2005) in press on the Appl. Phys. B

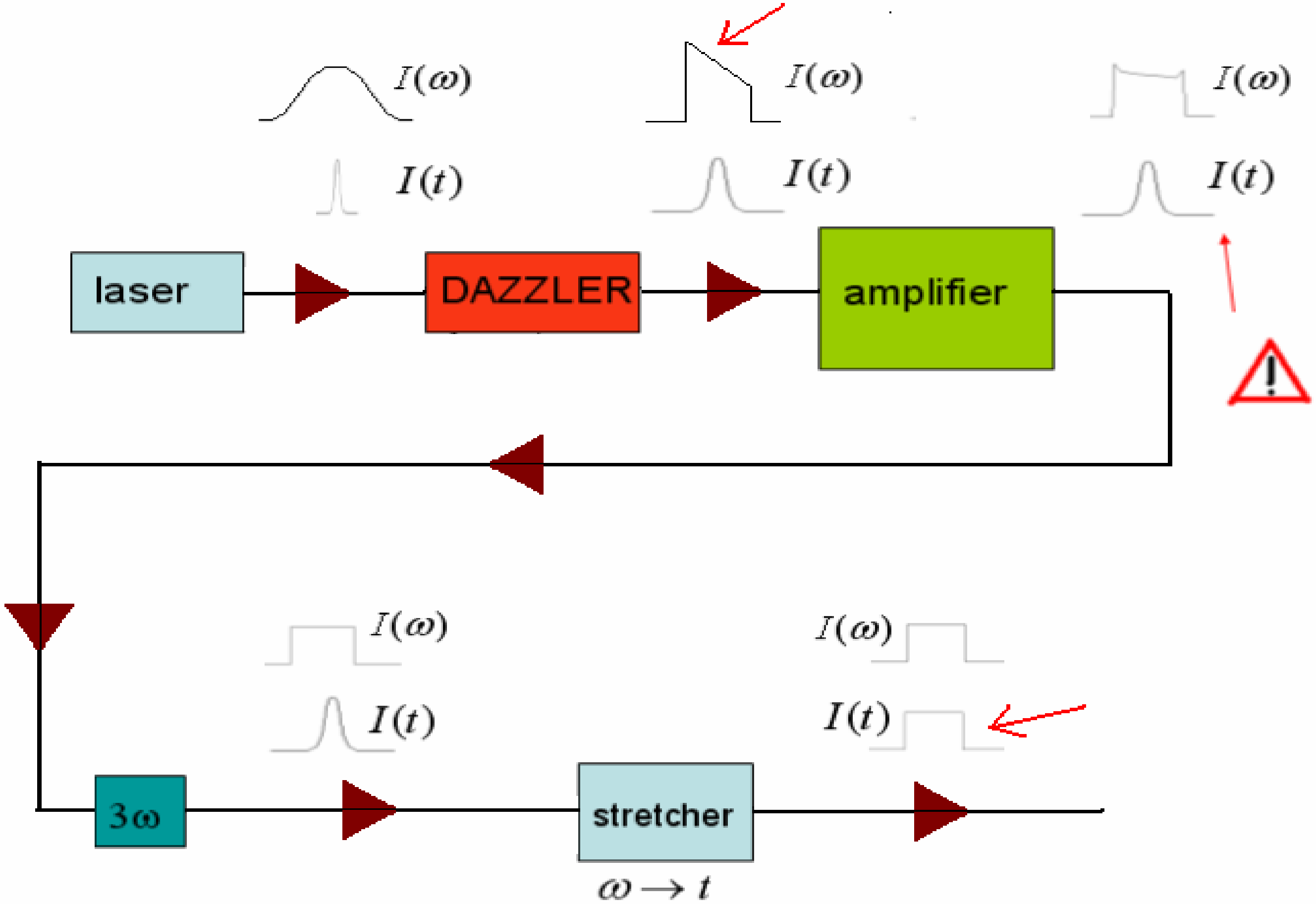
- The theory has been applied and positively tested at the SPARC apparatus in Frascati

- The relative simulation program developed in Milano have shown to be very useful for achieving experimentally the searched pulse waveform

- The high resolution spectrum analyzer developed in Milano has been reproduced in Frascati and has shown to be efficient for our needs

Pulse shaping at harmonics

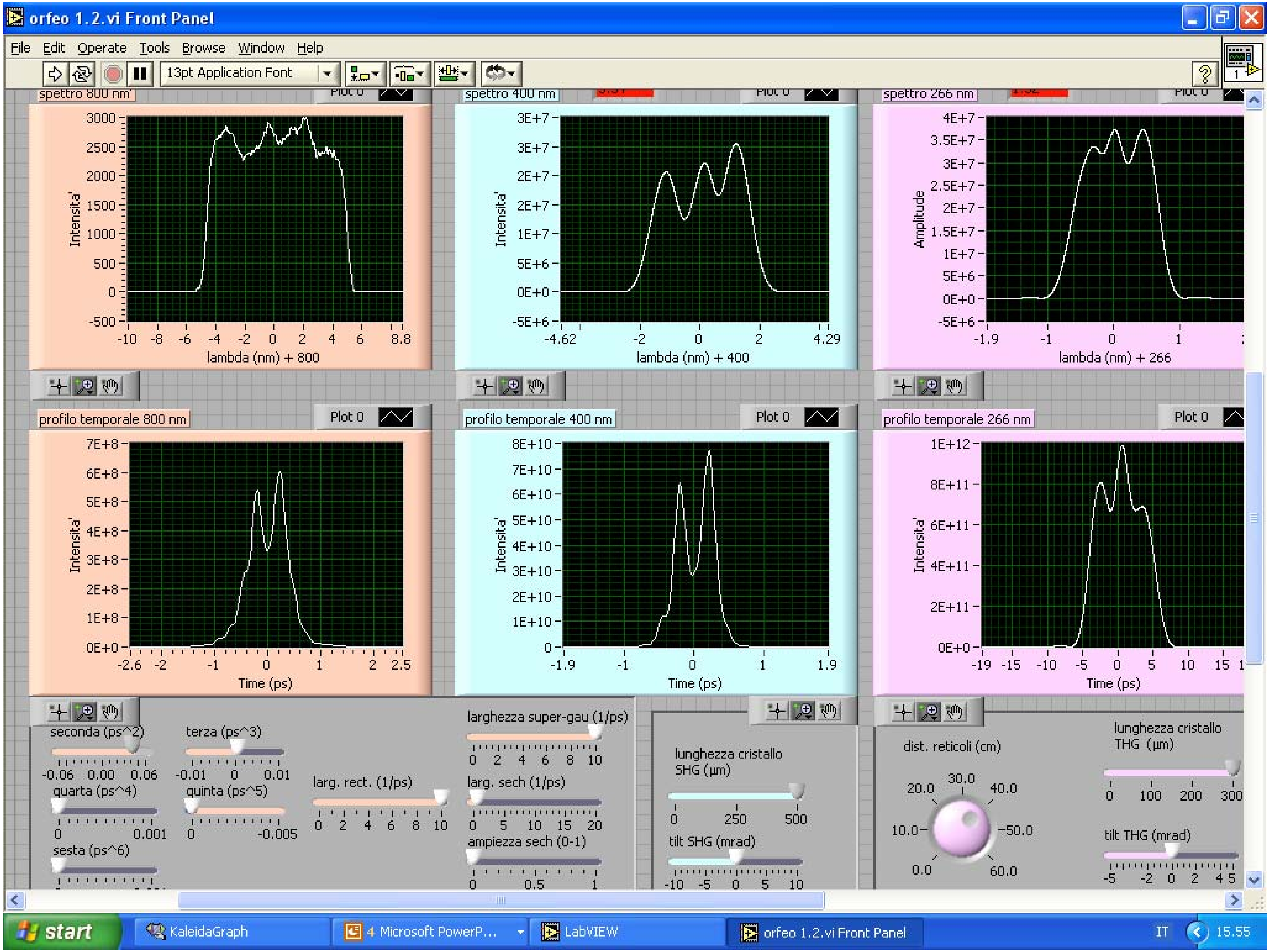
at SPARC laser system with DAZZLER



"Rectangular pulse formation in a laser harmonic generation", S.Cialdi, F. Castelli, I. Boscolo, Report INFN-BE-05-1 (2005) in press on the Appl. Phys. B

"A shaper for providing long laser waveforms" S. Cialdi, I. Boscolo, Nuc. Inst. Meth. A 538, 1-3 (2005) 1-7

$$I(t) \propto \left| \int A(\omega) \cdot e^{i\frac{1}{2}\alpha\omega^2} \cdot e^{-i\omega \cdot t} d\omega \right|^2 \approx \left| \int A(\omega) \cdot \delta\left(\omega - \frac{t}{\alpha}\right) d\omega \right|^2 = \tilde{I}\left(\omega(t)\right)$$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Plot 0
Time (ps)
profilo temporale 400 nm
profilo temporale 266 nm
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terza (ps^3)
quarta (ps^4)
quinta (ps^5)
sesta (ps^6)
larg. rect. (1/ps)
larghezza super-gau (1/ps)
larg. sech (1/ps)
ampiezza sech (0-1)
lunghezza cristallo SHG (µm)
tilt SHG (mrad)
dist. reticoli (cm)
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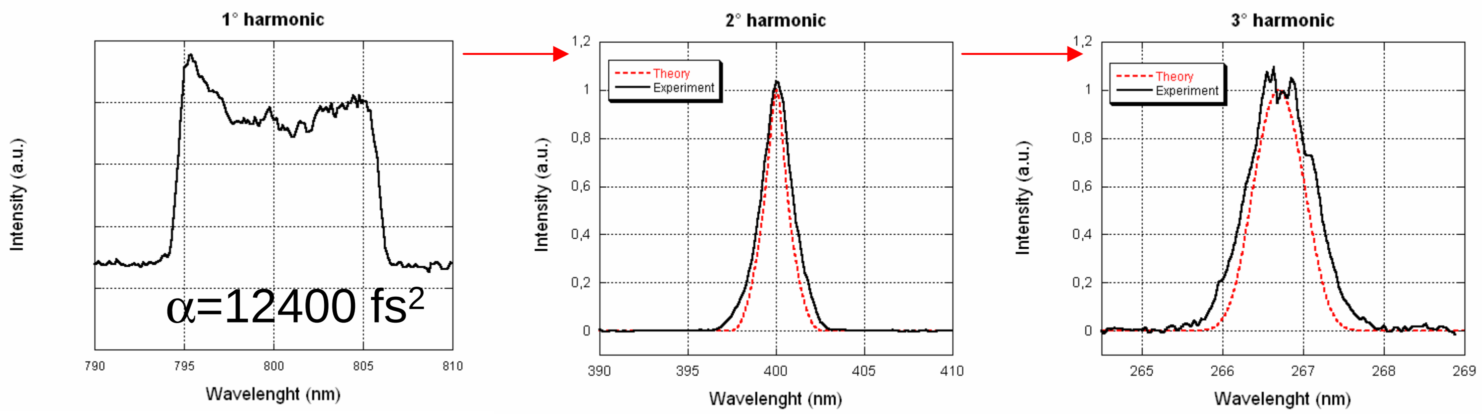
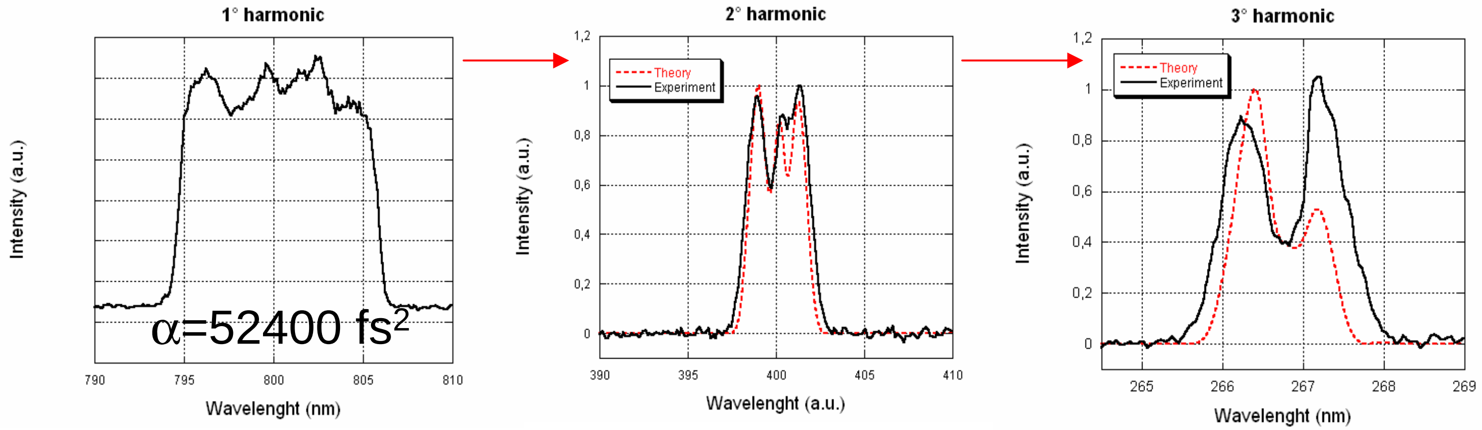
Comparison between theory and experiment

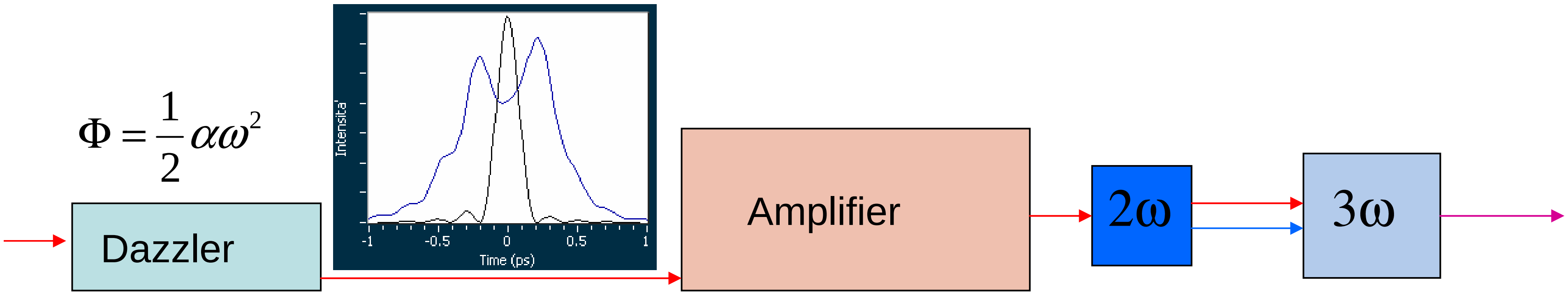


$$A_2(t) \propto A_1(t)^2$$
$$\downarrow$$
$$A_2(\omega) \propto A_1(\omega) \otimes A_1(\omega)$$

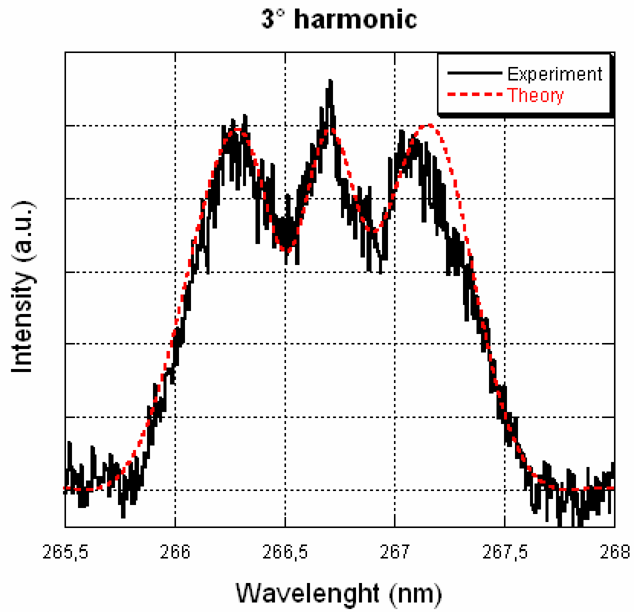


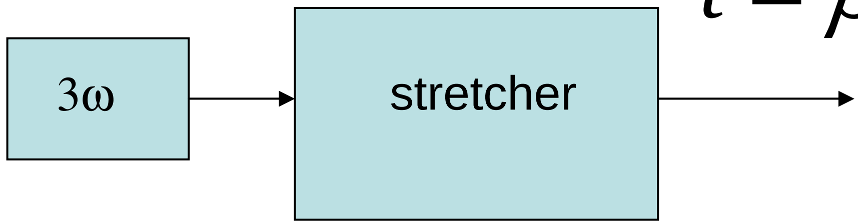
$$\alpha \to \infty$$
$$I_2(\omega) \approx I_1^{\,2}\left(\frac{\omega}{2}\right)$$

$$\Phi = \frac{1}{2}\alpha\omega^2$$



First rectangular spectrum in 3° harmonic





$$t = \beta \cdot \delta\lambda$$

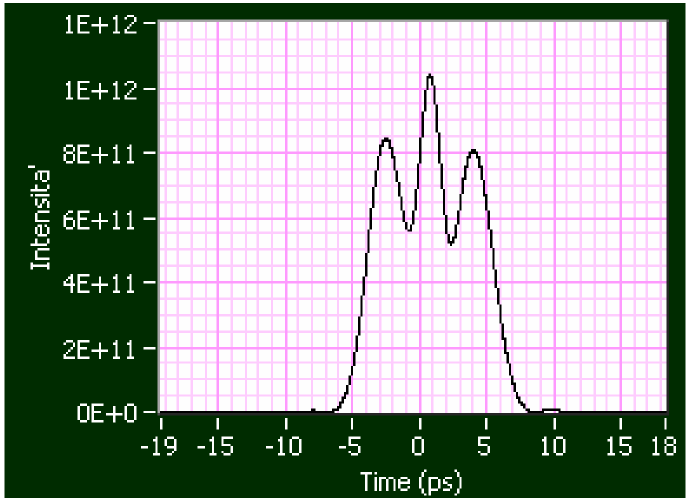
$$\tau_{rise-time} \approx 2.3\, ps$$

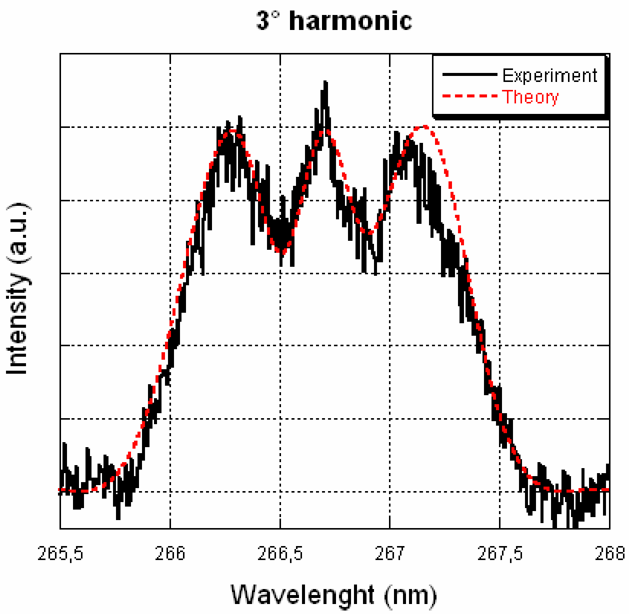
$\tau_{\text{rise-time}}$ (2.3 ps $\longrightarrow$ 1 ps)

$\Delta\Omega_3$ > constant (t_{min} < 1ps) this is not a problem

$\Delta\Omega_3 < \Delta\Omega_{crystal}$ (we have to reduce the spectrum width in 1° harmonic)

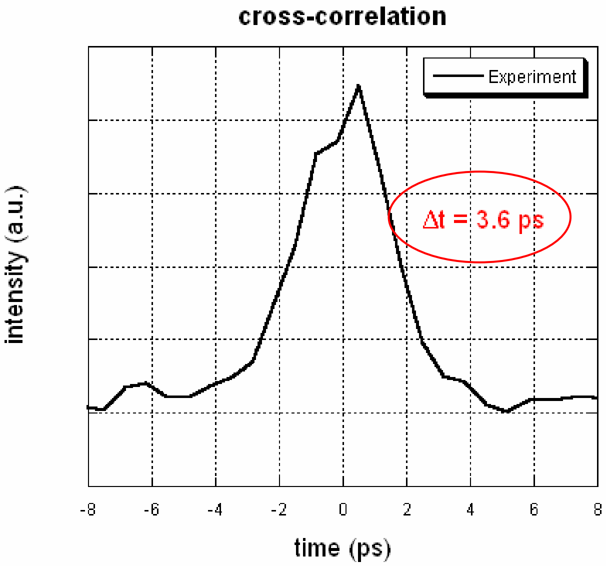
Cross Correlation measurements



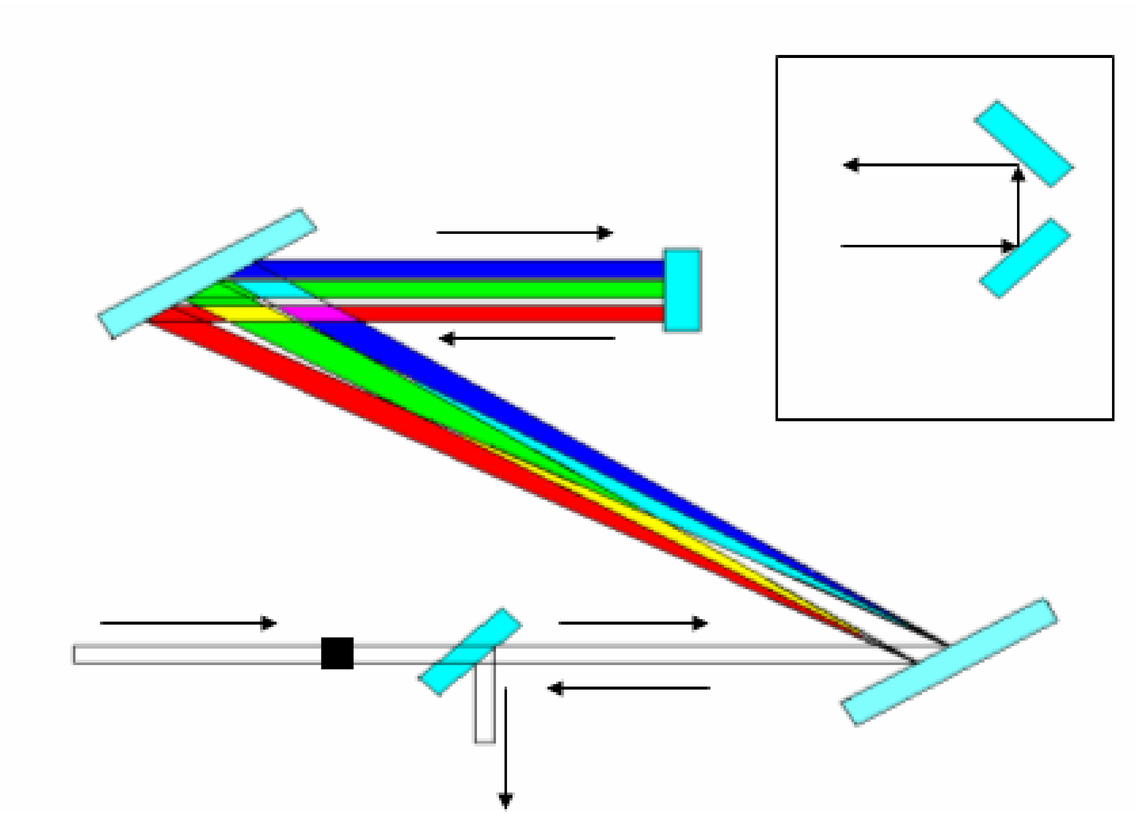


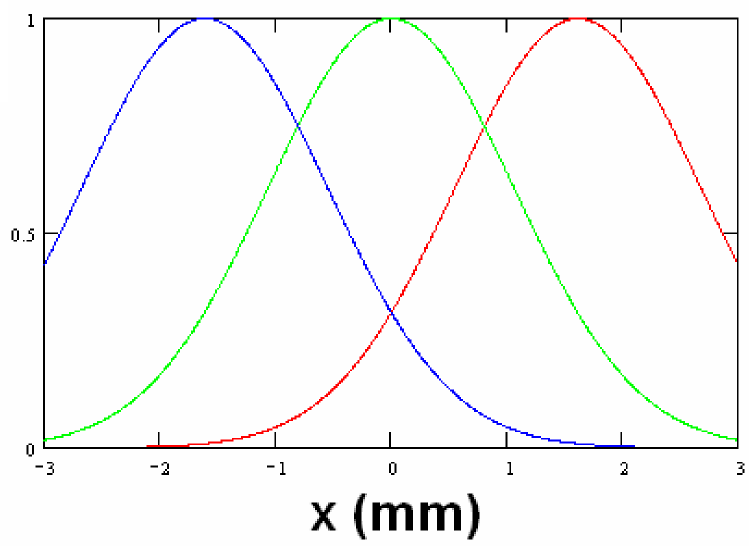
ω → t

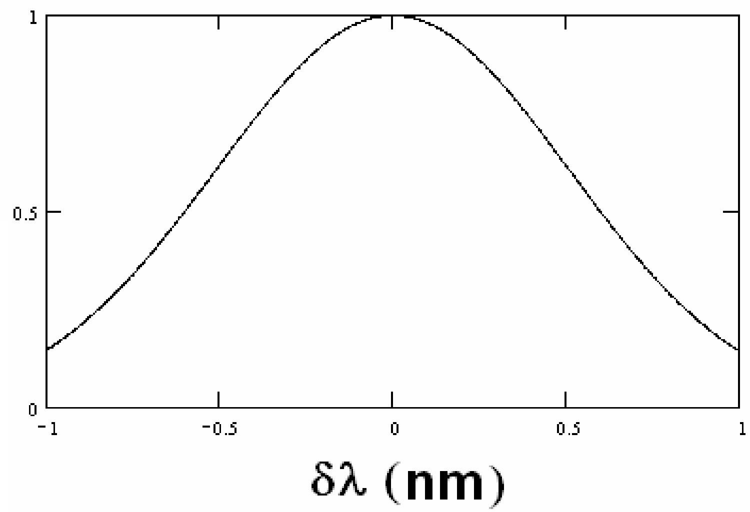
$$I(t) \approx I(\omega)$$



Spatial chirp







First comments about DAZZLER and LCM-SLM

- DAZZLER seems easier to menage than LCM for rectangular pulse generation
- LCM-SLM looks like more suitable for generation of a pulse train
- Spatial and spectral deformation due to the LCM diffraction effects

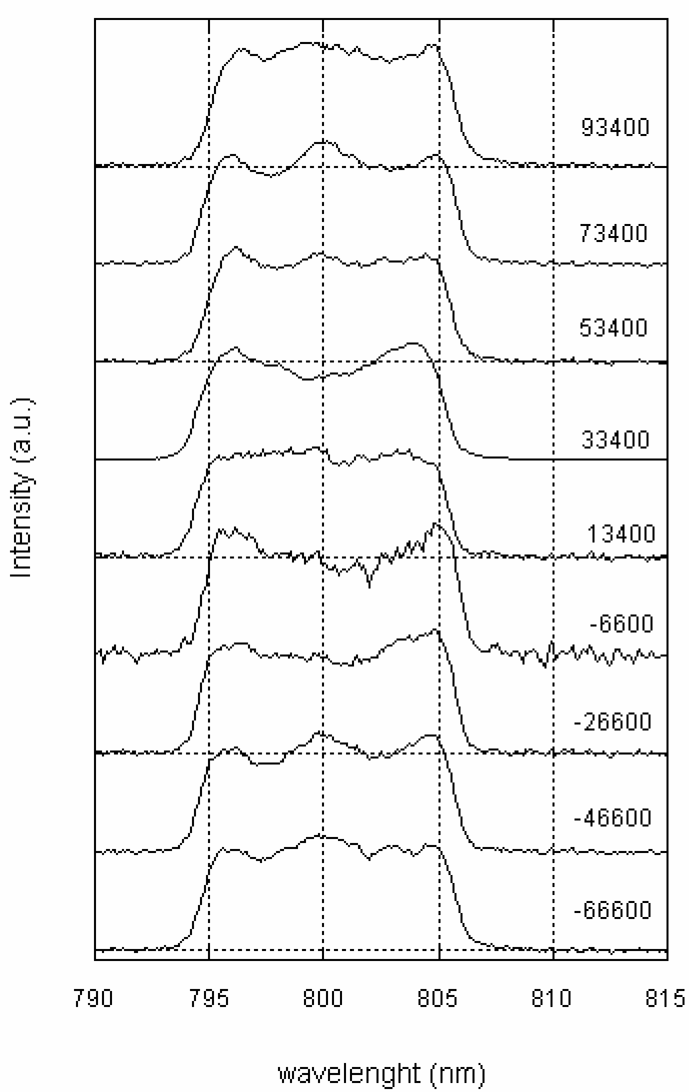
$$\Delta\tau_{LCM} \cdot \Delta\omega_{pixel} \leq \frac{2}{3}\pi$$

$$\Delta\tau_{LCM} > \Delta\tau_{DAZZLER}$$

- In the DAZZLER the amplitude and phase modulation are not decoupled

Dazzler amplitude modulation vs chirp

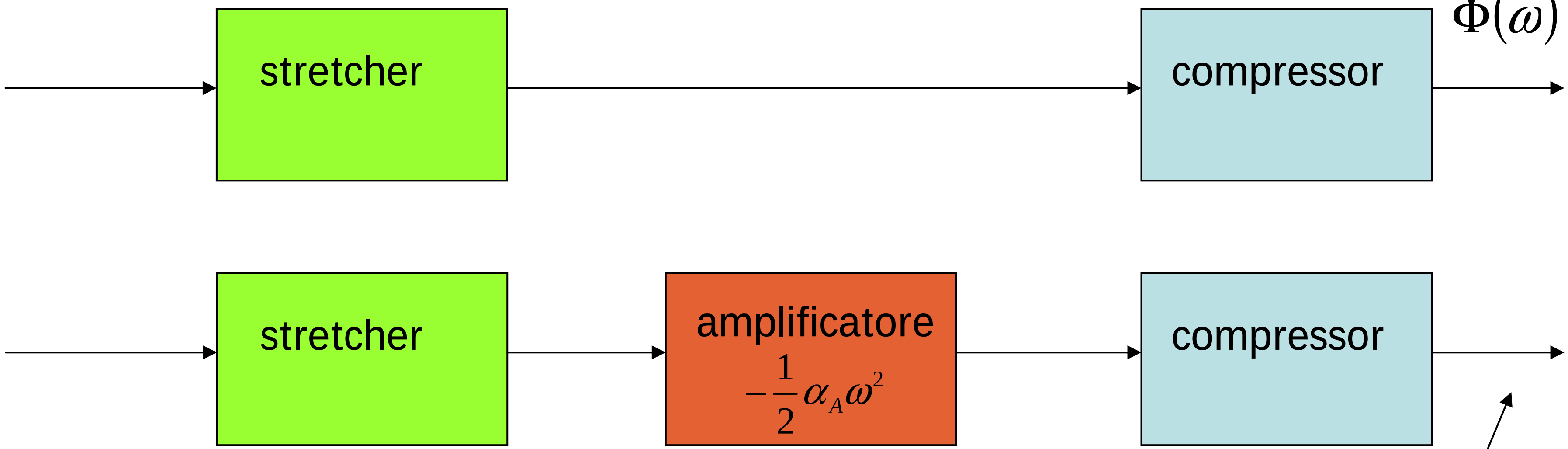
$$\Phi = \frac{1}{2}\alpha \cdot \omega^2$$



Amplifier phase function

$$\Phi(\omega) = -\frac{1}{2}\alpha_S\omega^2 - \frac{1}{3!}\beta_S\omega^3 - \frac{1}{4!}\gamma_S\omega^4 + \dots$$

$$\Phi(\omega) = 0$$



$$\frac{1}{2}(\alpha_C - \alpha_A - \alpha_S)\omega^2 = 0$$

$$\Phi(\omega) = \frac{1}{3!}(\beta_C - \beta_S)\omega^3 + \frac{1}{4!}(\gamma_C - \gamma_S)\omega^4 + \dots$$

Published articles about laser pulse shaping

- 5 papers
  - "A laser pulse shaper for the low-emittance radiofrequency SPARC electron gun", S. Cialdi, I. Boscolo, Nuc. Inst. Meth. A 526 (2004) 239-248
  - "Feature of a phase-only shaper set for a long rectangular pulse", S. Cialdi, I. Boscolo, A. Flacco, J. Opt. Soc. Am. B, 2, 1693 (2004)
  - "A shaper for providing long laser waveforms" S. Cialdi, I. Boscolo, Nuc. Inst. Meth. A 538, 1-3 (2005) 1-7
  - "Rectangular pulse formation in a laser harmonic generation", S.Cialdi, F. Castelli, I. Boscolo, Report INFN-BE-05-1 (2005) on press on the Appl. Phys. B
  - "An optical system developed for target laser pulse generation", S. Cialdi, I. Boscolo, A. Paleari, Report INFN-BE-05-2
- 3 papers in progress
  - Effects on the pulse shape of the 2° and 3° harmonic generation in the SPARC laser
  - Spatial and spectral deformation due to the LCM-SLM
  - Pulse train generation in 3° harmonic with the LCM-SLM to FEL radiation generation

Considerations

- The findings (theoretical, numerical, hardware) of Milano pulse shaping are implemented to SPARC experiment in Frascati.
- We will proceed on
  - Investigation of the action of the system non-linearities on the pulse profile
  - Investigation of the pulse train harmonic generation
  - Investigation of the spatial deformation due to the LCM diffraction effects
  - Comparison of the two systems: Dazzler-LCM
- The rise time is still an open problem which needs a development in Milano of hardware:
  - Cross-correlator and compressor
  - But for the harmonics Milano looks for some founding for an amplifier

$$\begin{cases} \dfrac{\partial A_1}{\partial z} + \dfrac{1}{Vg_1}\dfrac{\partial A_1}{\partial t} \approx 0 \\ \dfrac{\partial A_2}{\partial z} + \dfrac{1}{Vg_2}\dfrac{\partial A_2}{\partial t} \approx 0 \\ \dfrac{\partial A_3}{\partial z} + \dfrac{1}{Vg_3}\dfrac{\partial A_3}{\partial t} = i\gamma A_1 A_2 e^{-i\Delta k \cdot z} \end{cases}$$

$$\Delta k \approx \alpha \cdot \theta$$

Rectangular pulse formation in a laser harmonic generation, S.Cialdi, F. Castelli, I. Boscolo, Report INFN-BE-05-1 (2005), in press. on Appl. Phys. B

appendix

$$A_1 = A_1\left(t - \frac{z}{Vg_1}\right) \qquad A_2 = A_2\left(t - \frac{z}{Vg_2}\right)$$

$$\frac{\partial A_3}{\partial z} + \frac{1}{Vg_3}\frac{\partial A_3}{\partial t} = i\gamma A_1\left(t - \frac{z}{Vg_1}\right)\cdot A_2\left(t - \frac{z}{Vg_2}\right)\cdot e^{-i\Delta k\cdot z}$$

$$\tau = t - \frac{z}{Vg_3} \qquad \beta_{ij} \equiv \frac{1}{Vg_i} - \frac{1}{Vg_j}$$

$$\frac{\partial A_3}{\partial z} = i\gamma A_1\left(\tau + \beta_{31}\cdot z\right)\cdot A_2\left(\tau + \beta_{32}\cdot z\right)\cdot e^{-i\Delta k\cdot z}$$

$$\frac{\partial \tilde{A}_3}{\partial z} = i\gamma\left[\left(\tilde{A}_1 \cdot e^{-i\beta_{31} z\omega}\right) \otimes \left(\tilde{A}_2 \cdot e^{-i\beta_{32} z\omega}\right)\right] \cdot e^{-i\Delta k \cdot z}$$

$$\beta_{ij} - \beta_{il} = -\beta_{jl}$$

$$\frac{\partial \tilde{A}_3}{\partial z} = i\gamma\left[\tilde{A}_1 \otimes \left(\tilde{A}_2 \cdot e^{i\beta_{21} z\omega}\right)\right] \cdot e^{-i\left(\beta_{31}\omega + \Delta k\right) \cdot z}$$

$$\frac{\partial \tilde{A}_3}{\partial z} = i\gamma\left[\tilde{A}_1 \otimes \left(\tilde{A}_2 \cdot e^{i\beta_{21} z\omega}\right)\right] \cdot e^{-i\left(\beta_{31}\omega + \Delta k\right)\cdot z}$$

$$\frac{\partial \tilde{A}_3}{\partial z} \approx i\gamma \cdot \left[\tilde{A}_1 \otimes \tilde{A}_2\right] \cdot e^{-i\left(\beta_{31}\omega + \Delta k\right)\cdot z}$$

$$\tilde{A}_3 \approx i\gamma \cdot z \cdot \left(\frac{e^{-i\beta_{31}\left(\omega + \frac{\Delta k}{\beta_{31}}\right)\cdot z} - 1}{-i\beta_{31}\left(\omega + \frac{\Delta k}{\beta_{31}}\right)\cdot z} \right) \cdot \left[\tilde{A}_1 \otimes \tilde{A}_2\right]$$

appendix

$$\left[\tilde{A}_1 \otimes \tilde{A}_2\right] \to \left[\tilde{A}_1 \otimes \tilde{A}_1\right]$$

$$\tilde{A}_1(\omega) = S_1(\omega) \cdot e^{i\frac{1}{2}\alpha\omega^2}$$

$$A_2(\omega) \propto \left[\tilde{A}_1 \otimes \tilde{A}_1\right] = \int S_1(\omega-\omega')S_1(\omega') \cdot e^{i\frac{1}{2}\alpha\left[(\omega-\omega')^2+\omega'^2\right]} d\omega' \approx$$

$$\int S_1(\omega-\omega')S_1(\omega') \cdot e^{i\frac{1}{2}\alpha\left[(\omega-\omega')^2+\omega'^2\right]} \delta\left(\omega'-\frac{\omega}{2}\right) d\omega' = S_1^2\left(\frac{\omega}{2}\right) e^{i\alpha\left(\frac{\omega}{2}\right)^2}$$