Cross polarized wave generation – a nonlinear optical method for cleaning femtosecond pulses

S. Kourtev, N. Minkovski, S. M. Saltiel
Faculty of Physics, University of Sofia, 5 J. Bourchier Boulevard, BG-1164, Sofia, Bulgaria

L. Canova, O. Albert, A. Jullien
Laboratoire d'Optique Appliquée, ENSTA , Ecole Polytechnique, CNRS UMR 7639, 91761 Palaiseau Cedex, France

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Cross-Polarized Wave generation is

Third order non linear process - FWM:

- **degenerate in frequencies**
- **non degenerate in polarization**

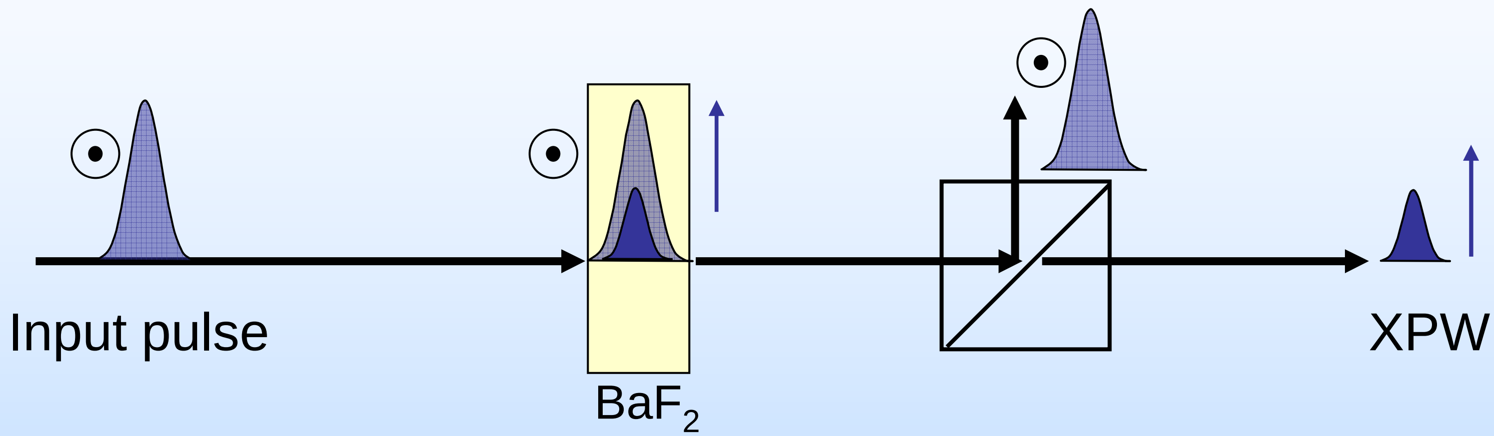
$$\omega_{out}^{(\perp)} = \omega^{(//)} + \omega^{(//)} - \omega^{(//)}$$

- Wavelength conservation (the generated wave is at the same wavelength as the input one);
- In crystals with anisotropy of the $\chi^{(3)}$ tensor;

$$\sigma = \frac{\chi_{xxxx}^{(3)} - \left[\chi_{xxyy}^{(3)} + 2\chi_{xyyx}^{(3)}\right]}{\chi_{xxxx}^{(3)}} \neq 0$$

- Automatically phase matched over large bandwidth (the same phase velocities and the same group velocities for fundamental wave and XPW)

The basic idea of the XPW generation process



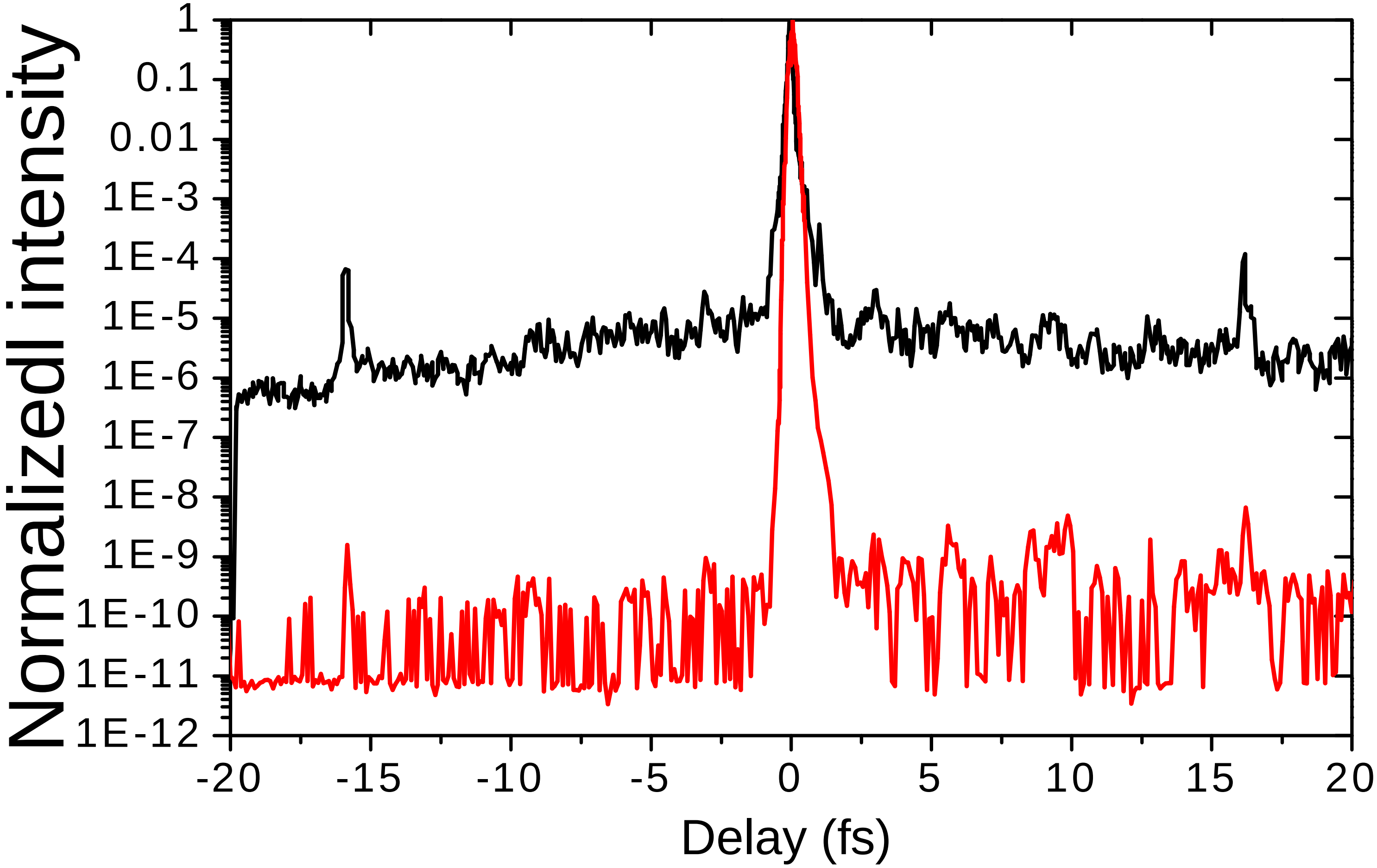
$$E(t) \xrightarrow{\chi^{(3)}} \left|E(t)\right|^2 E(t)$$

N. Minkovski, JOSA B 21 (2004).

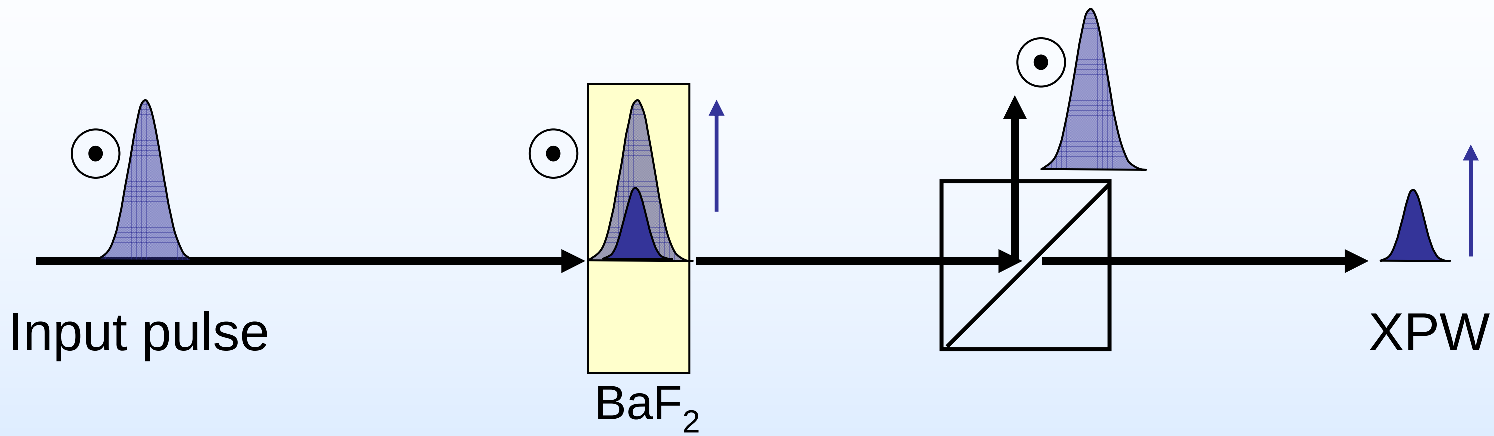
NONLINEAR OPTICAL 90^{o} “ROTATION” OF LIHGT POLARIZATION PLANE

main results

I. Increased temporal contrast by 4..5 orders



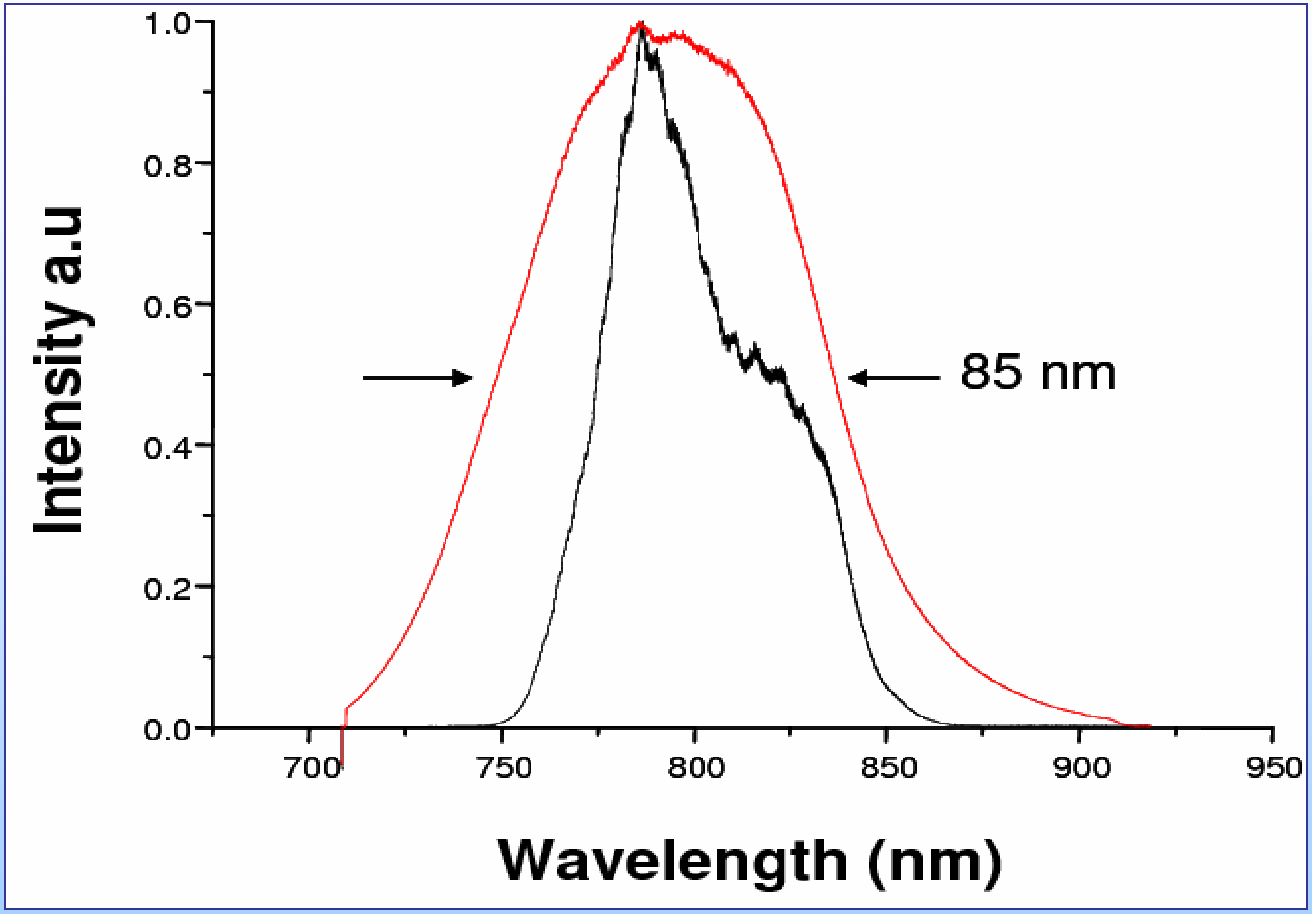
OTHER WAYS TO CHARACTERIZE



NONLINEAR OPTICAL INTENSITY DEPENDENT 90º POLARIZATION ROTATION

ALL OPTICAL SELF INDUCED POLARIZATION SWITCHING

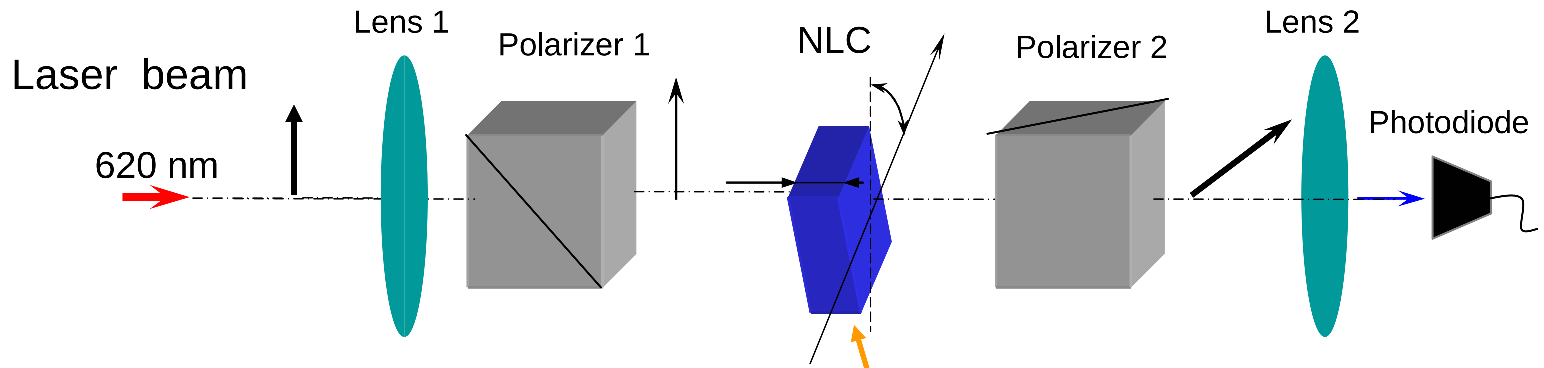
II. Spectral broadening and filtering. Respective pulse duration compression ~ 2 times.



III. Phase flattering

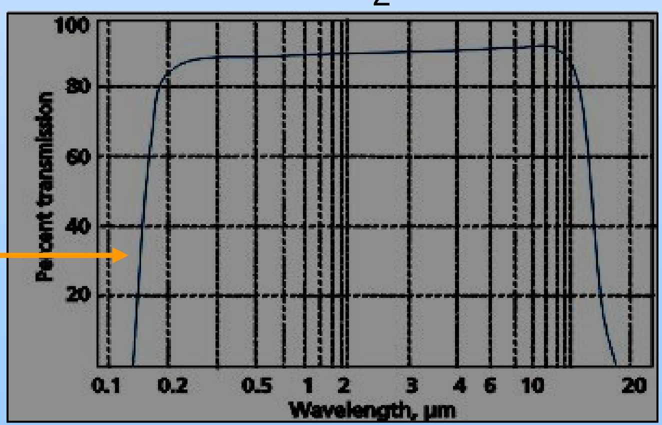
IV. Improvement of the spatial distribution as well

Experimental setup



BaF_2

Cut-off: 135 nm



Perfect to be used for any wavelength in transparency region

Cross-polarized wave generation by $\chi^{(3)}:\chi^{(3)}$ cascading

A - input wave
B - XP output wave

$$\eta = \left|\frac{B}{A}\right|^2 = 4\left|\frac{\gamma_\perp}{\gamma_{II}}\right|^2 \sin^2\left(\gamma_{II}|A|^2 L/2\right)$$

And for $\gamma_{II}|A|^2 L << 1$

$$B = \gamma_\perp |A|^2 AL$$

$$\eta = \left(\gamma_\perp |A|^2 L\right)^2$$

XPW generation is result of the cubic process B - AAA where all waves has the same frequency, but wave B is perpendicularly polarized to wave A , indeed FWM

Cross-polarized wave generation by $\chi^{(3)}:\chi^{(3)}$ cascading

For arbitrary input intensity (arbitrary $\gamma_{II}|A|^2 L$)

the following system has to be numerically solved:

$$\frac{dA}{dz} = i\gamma_1|A|^2 A - i\gamma_2\left(|B|^2 B - A^2 B^* - 2|A|^2 B\right) + i\gamma_3\left(B^2 A^* + 2|B|^2 A\right)$$

$$\frac{dB}{dz} = i\gamma_1|B|^2 B + i\gamma_2\left(|A|^2 A - B^2 A^* - 2|B|^2 A\right) + i\gamma_3\left(A^2 B^* + 2|A|^2 B\right)$$

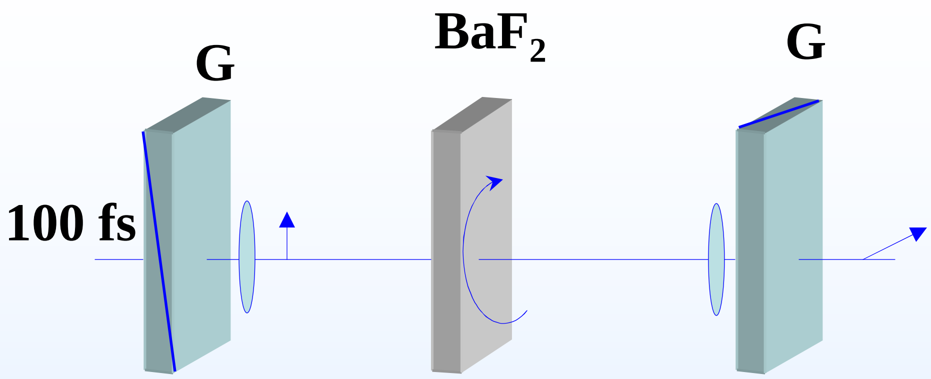
SPM

XPW generation

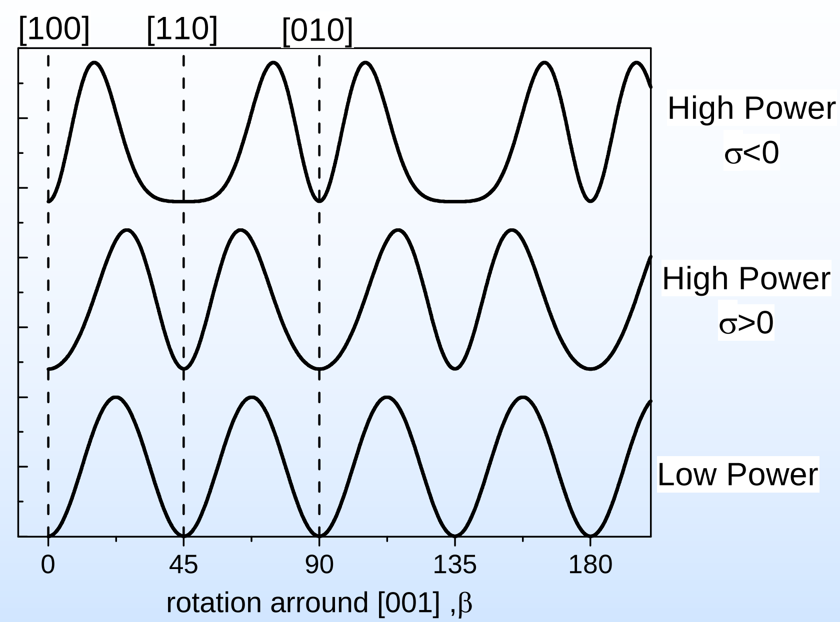
B <–> A energy transfer

CPM

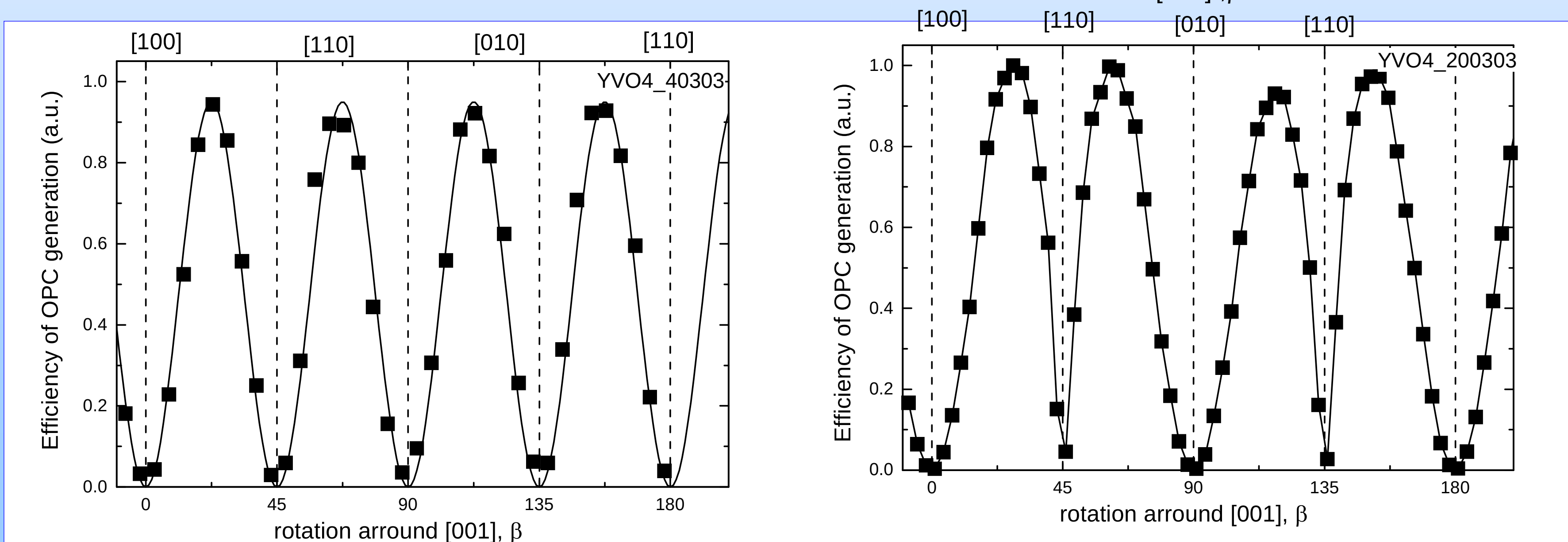
Practically all $\chi^{(3)}$ processes involved in the full theoretical description



8 fold curves

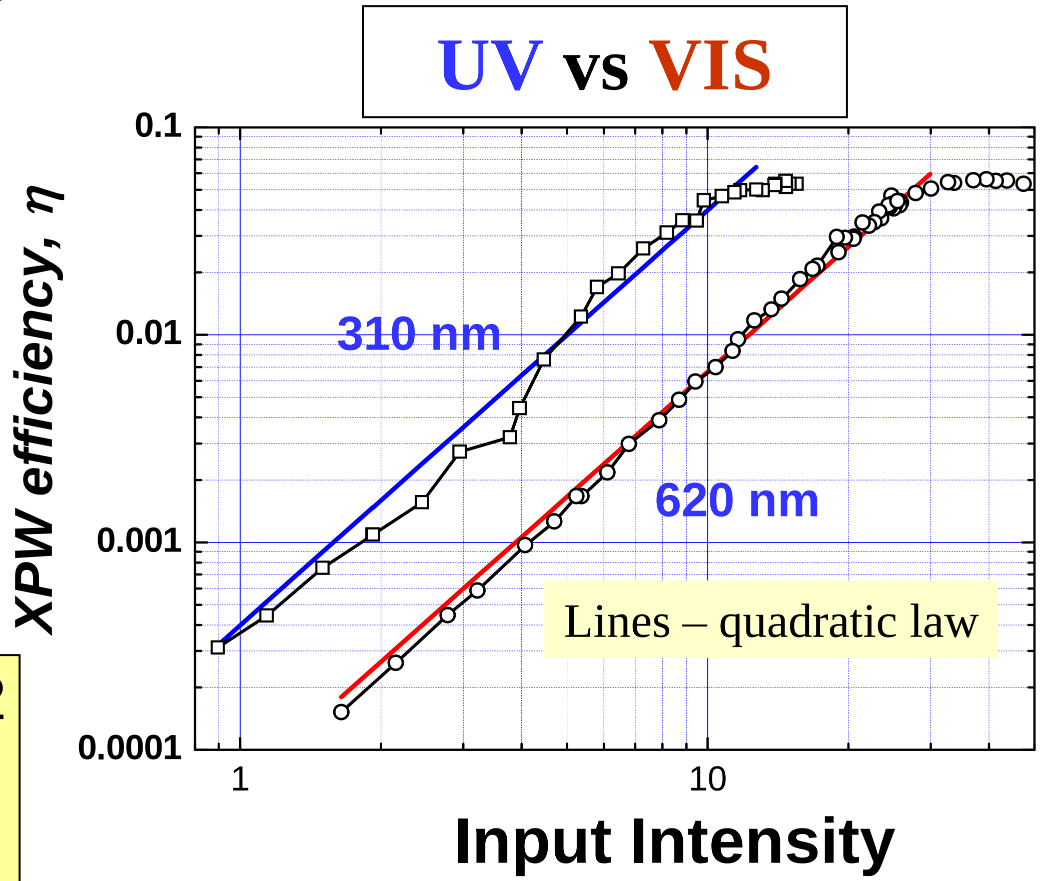


Nonlinear crystal has to be rotated at angle that maximize the XPW signal ~ $\pi/8+m\pi/2$



Experimental results for
XPW generation efficiency with BaF_2 crystal

XPW generation is more then 6 times more efficient at 310 nm compared to 620 nm



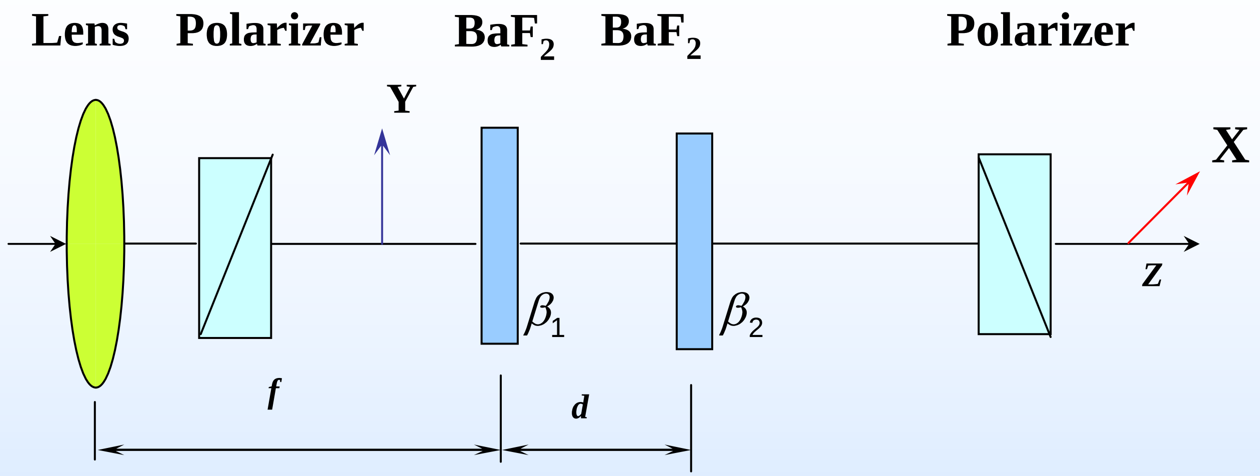
$$\eta(\lambda) \geq \eta(\lambda_o)\left(\frac{\lambda_o}{\lambda}\right)^2$$

Holographic cut of the crystal – gives best efficiency

Up to now only Z-cut was used. Holographic cut is our most recent discovery. Will be published in APL in June 2008

Holographic cut notation is [011]

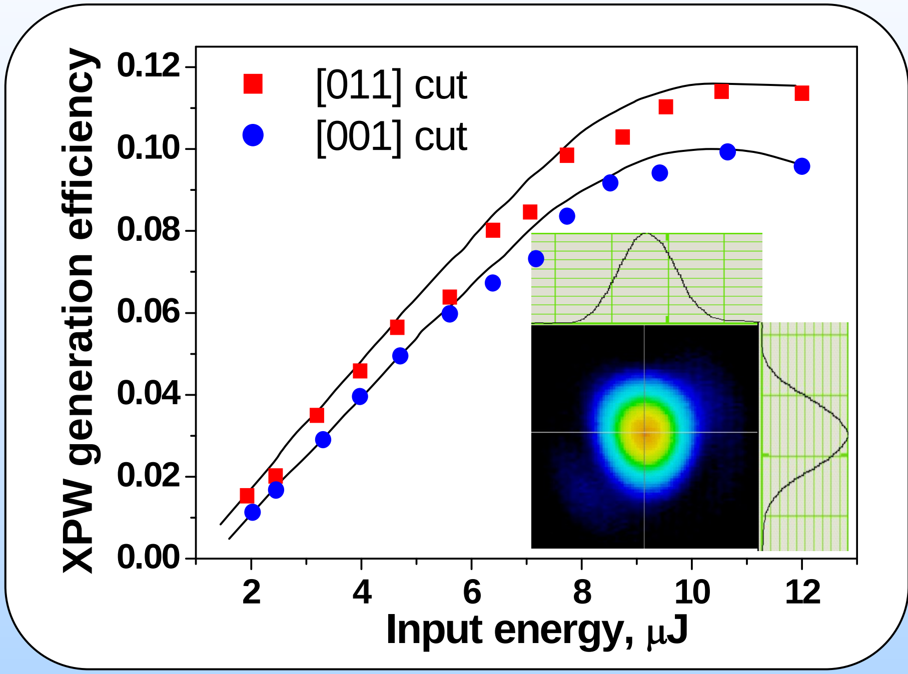
Z - cut notation is [001]

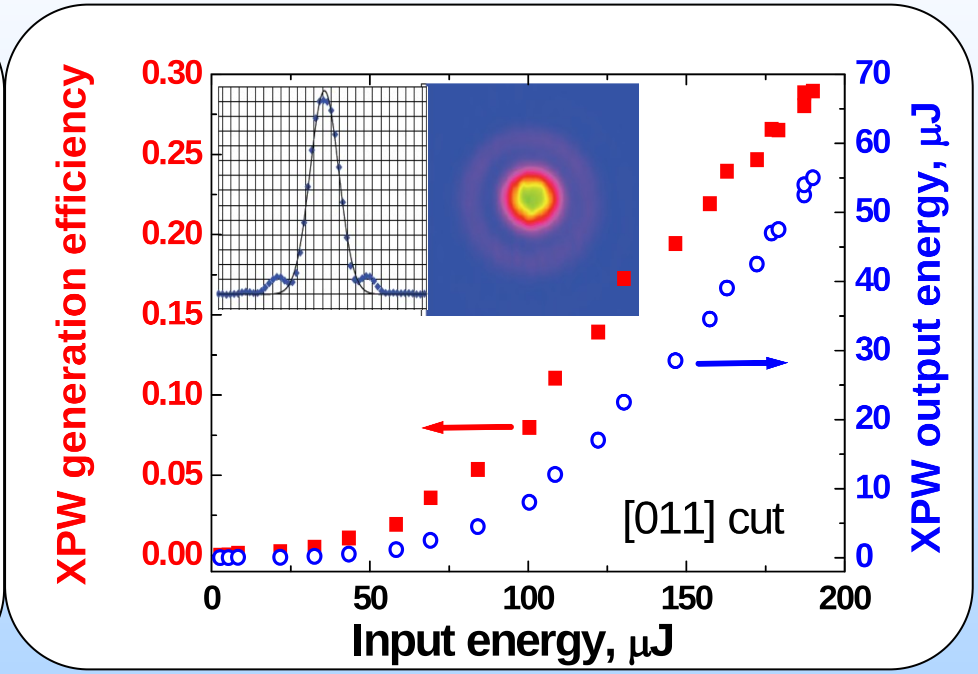


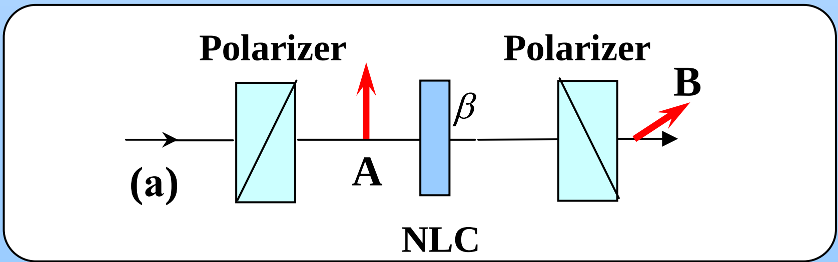
Solution – two crystal arrangement

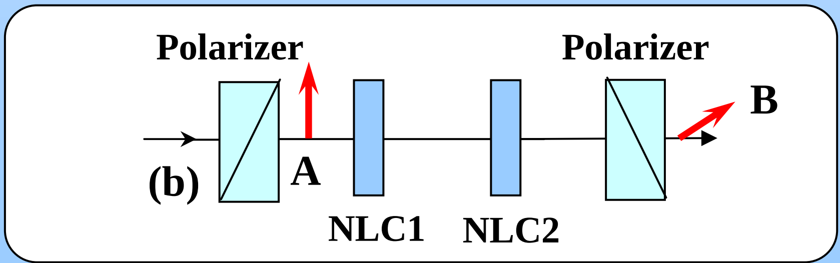
two crystal distance d – set to optimal

Holographic cut XPW generation









Femtosecond pulses by XPW generation:

- ► Better contrast - improved by 10^4 .. 10^5 times;
- ► Pulse duration 1.5 ..2.5 times shorter;
- ► Spectral shape smoother and symmetric;
- ► Redused spectral phases – i. e. better TBP;
- ► Improved spatial shape.

XPW generation improves drastically all parameters of the input femtosecond pulses

Femtosecond pulses by XPW generation are perfect for medical applications where the fs parameters are important

Such application is: proton beam therapy

Medical Physics -- May 2008 -- Volume 35, Issue 5, pp. 1770-1776

Accelerating Protons to Therapeutic Energies with Ultra-Intense Ultra-Clean and Ultra-Short Laser Pulses

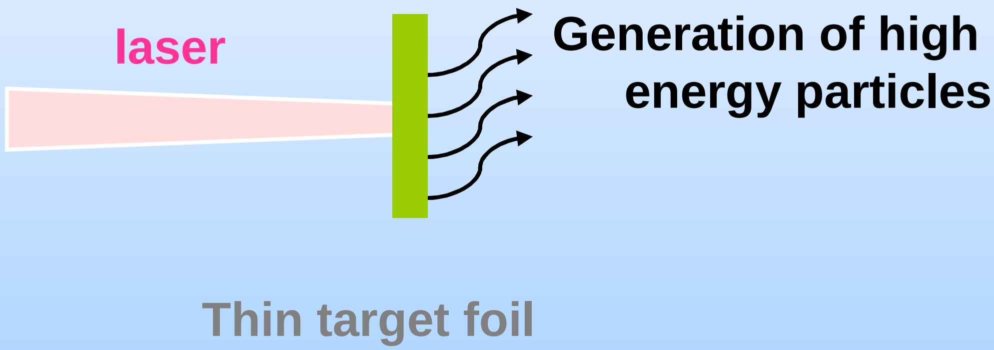
Stepan S. Bulanov[1], Andrei Brantov[2], Valery Yu. Bychenkov[2], Vladimir Chvykov[1], Galina Kalinchenko[1], Takeshi Matsuoka[1], Pascal Rousseau[1], Stephen Reed[1], Victor Yanovsky[1], Karl Krushelnick[1], Dale William Litzenberg[3] and Anatoly Maksimchuk[1]

FOCUS Center and Center for Ultrafast Optical Science, University of Michigan

Proton beam therapy has a physical advantage over gamma rays and x-rays when it comes to dosage deposition in healthy tissues. This energy can be very precisely controlled to place the Bragg peak within a tumor or other tissues that are targeted to receive the radiation dose. Because the protons are absorbed at this point, healthy tissues beyond the target receive very little or no radiation.

FROM the presentation of **S. A. Reed , UM**

High Intensity Laser Solid Interactions Require high contrast



ASE pedestal modify the conditions of the interaction

Needed 10^{22} W/cm^2 laser power

for 250 MEV beam of protons

FROM the presentation of Dale William Litzenberg , UM

Background

- Therapeutic proton energies require very high laser intensities & thin target foils ($E_{max} \sim I_p^{1/2} / t$)
- Target thickness is limited by target damage from Amplified Spontaneous Emission (ASE) prepulse
- Contrast, $c = I_{ASE} / I_P$ (typically $10^{-5} – 10^{-8}$)
- Must have large enough I_P to reach therapeutic proton energies, and sufficient contrast, c, so that I_{ASE} is low enough to preserve target integrity

FROM the thesis of **S. A. Reed, p. 32**

ELECTRON AND PROTON ACCELERATION USING THE 30 TW, 30 fs HERCULES LASER

by
Stephen A. Reed

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy
(Applied Physics)

in The University of Michigan
2008

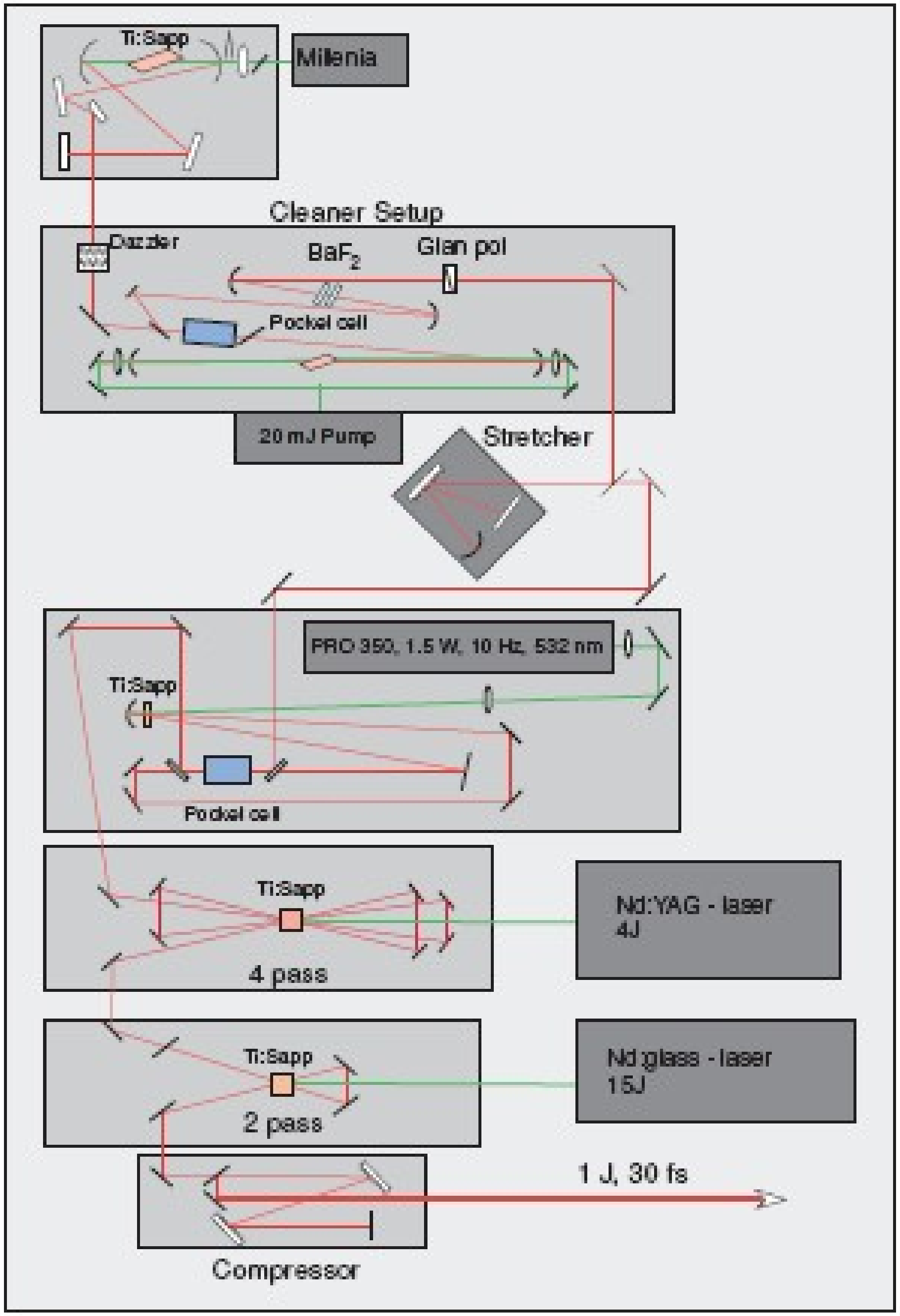


Figure 3.2: Schematic of the HERCULES laser system.

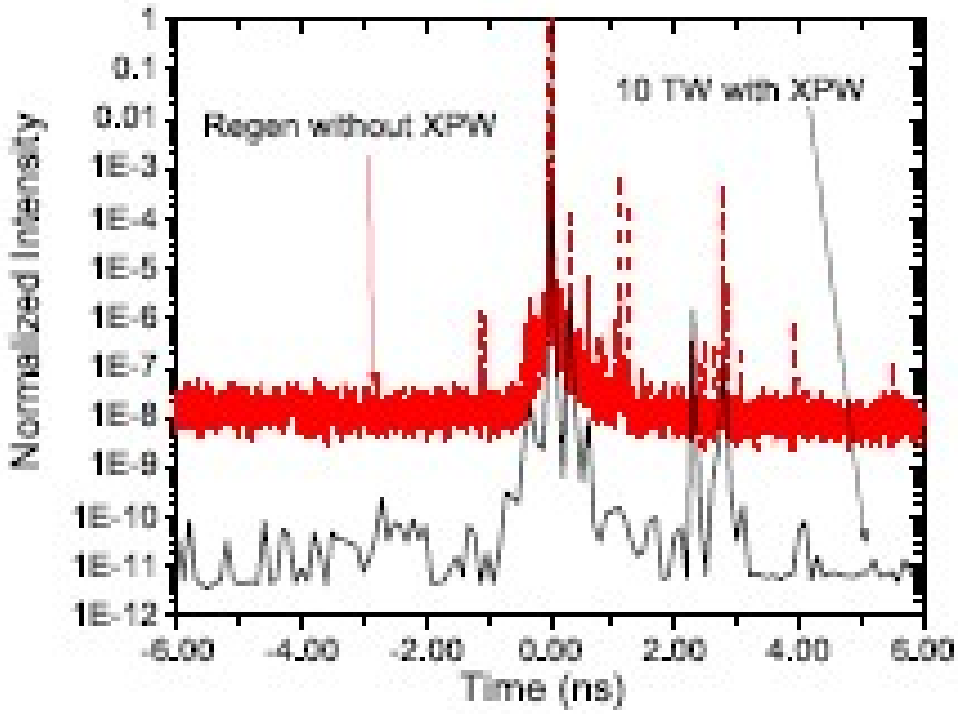


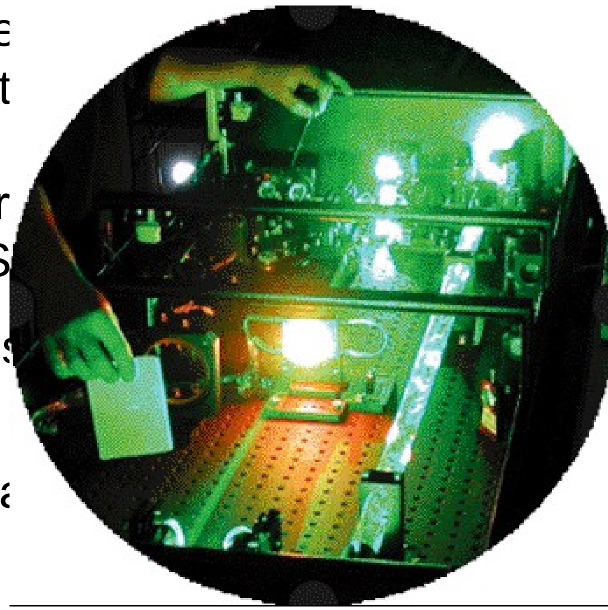
Figure 3.8: Third-order autocorrelation without (top red curve - regenerative amplifier only) and with (bottom black curve - 10 TW power) the XPW cleaner.

FROM the thesis of **S. A. Reed, p. 42**

COMPANIES INCLUDE XPW SET – UP AS AN OPTION FOR THE TW FS LASERS

THALES ALPHA 10

Alpha 10 is the demonstration of THALES Laser's expertise in ultra high intensity Ti:Sa lasers with the highe the market.
Alpha 10 integrates the lat e best performances, such as:



• Unsurpassed stability for HALES Laser's SAGA pump lasers and the use of DPS

• Sub 25 fs pulse duration ctral aperture stretcher/compressor and

• Water cooled laser cryst vative solution to overcome the thermal effects,

• **Unmatched picosecond contrast for laser-matter interaction experiments with our patented XPW technique.**

O. Albert, J. Etchepare, A. Jullien, G. Cheriaux, S. M. Saltiel and N. Minkovski, "Filtre non lineaire d'impulsions femtosecondes a contraste eleve." **Patent** (French, European and US-_#20060170858), date issued 30/11/2004. publication number: 2 878 657 (int Cl: H 01 S 3/10)

THALES 45TW laser with XPW contrast improvement system

XPW contrast improvement system

University of Texas Tri-Color Terawatt (UT3) Laser System

Conclusions and prospects

- XPW generation is a promising method for cleaning of femtosecond pulses;
- XPW pulse is compressed up to 2.5 times.
- Holographic cut BaF2 is the most efficient nonlinear media for XPW generation;
- The efficiency of the process is increasing with decreasing the wavelength

$$\eta(\lambda) \geq \eta(\lambda_o)\left(\frac{\lambda_o}{\lambda}\right)^2$$

Another promising application

Measuring the parameters of femtosecond pulses

By performing third order autocorrelation based on XPW generation process

main advantage we stay at the same wavelength

(in contrast to SHG methods)

Main publications

1. Canova, S. Kourtev, N. Minkovski, A. Jullien, R.Lopez-Martens, O. Albert, S. Saltiel, "Efficient generation of cross-polarized femtosecond pulses in cubic crystals with holographic cut orientation," Applied Physics Letters Volume 92, Issue 23, accepted (2008).

2. *A. Jullien, O. Albert, G. Cheriaux and J. Etchepare, S. Kourtev, N. Minkovski and S. M. Saltiel* ," Highly efficient temporal cleaner for femtosecond pulses based on cross-polarized wave generation in a dual crystal scheme, " Appl. Phys. B **84,** 409 - 414 (2006).

3. *A. Jullien, O. Albert, G. Cheriaux and J. Etchepare, S. Kourtev, N. Minkovski and S. M. Saltiel* "A two crystal arrangement to fight efficiency saturation in cross-polarized wave generation" Opt. Express **14 ,** 2760-2769 (2006)

4. *A. Jullien, O.Albert, F. Burgy, G. Hamoniaux, J-P. Rousseau, J-P Chambaret, F. Augé-Rochereau, G. Chériaux, J. Etchepare, N. Minkovski and S. M. Saltiel,* “10-10 temporal contrast for femtosecond ultraintense lasers by cross-polarized wave generation”. Optics Letters V 30, No 8, p 920-922, (2005).

5. *N.Minkovski , G.I. Petrov, S.M.Saltiel, O.Albert , J.Etchepare,* "Nonlinear Polarization Rotation and orthogonal Polarization Generation Experienced in a Single Beam Configuration", J.of Opt. Soc. Am. B, vol. 21, pp1659-1665(2004)

6. *N. Minkovsky , S. M. Saltiel, G.I. Petrov, O. Albert , J. Etchepare*, "Polarization Rotation Induced By Cascaded Third-Order Processes", Opt. Lett., vol. 27 pp. 2025-2027 (2002).

THANK YOU VERY MUCH