Laser pulse shaping for electron photoinjector

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Outline

- Introduction
  - Technical requirements to laser drivers for electron photoinjectrors
  - Tasks requiring laser pulse shaping
  - Used methods for pulse shaping in IR region
  - Pulse shape retaining at second and fourth harmonic generation
    - Angular chirping
    - Non collinear interaction of laser pulses with opposite frequency chirps
  - Prospects for using the photoinjector at IAP RAS

Modern acceleration centers

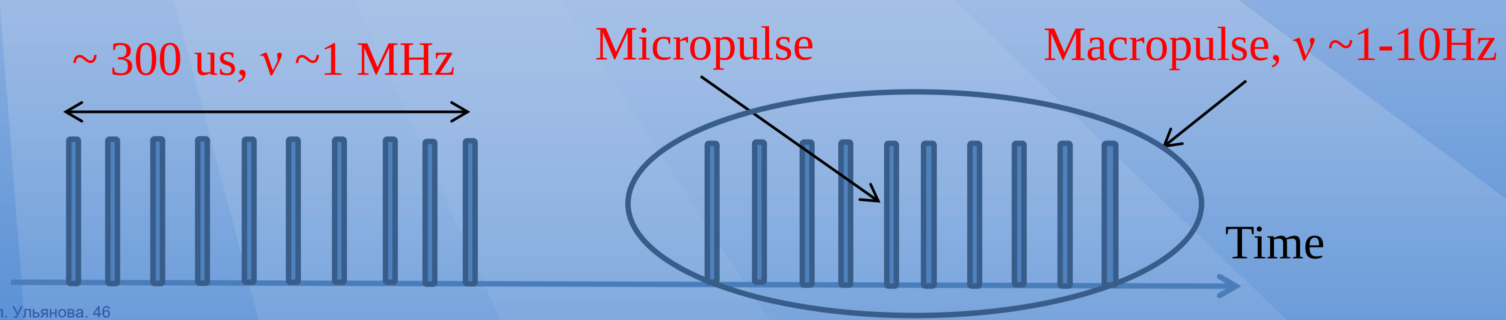
- Photo Injector Test Facility at DESY, Zeuthen, Germany (PITZ)
- The High Energy Accelerator Research Organization, KEK, Japan
- Stanford Linear Accelerator, USA
- Argonne National Laboratory, USA
- Joint Institute for Nuclear Research, Dubna, Russian Federation
- Institute of Applied Physics RAS (under construction)

Typical parameters of electron bunches at the output of photoinjector :

Charge ~ 0.1-1 nC
Duration ~ 7-50 ps
Normalized transversal emittance <1mm·mrad
Energy ~ 3-4 MeV

Requirements to laser pulses

- UV (for Cs_2Te), visible (cesium antimonide Cs_3Sb) region
- Micropulse energy 0.5-2 uJ on a cathode surface
- Duration7-50 ps, with a possibility to vary it
- 3D shaping of each micropulse



Tasks requiring laser pulse shaping
(in application to photoinkectors)

- **Reducing the transverse emittance of the electron beam due to control of space charge distribution**
  - Formation of laser pulses with cylindrical and 3D ellipsoidal intensity distribution
- **Energy transition from a drive beam to a witness through a wake field in electrodynamic structures**
  - Formation of quasi-triangular laser pulses
- **Generation of THz pulses in undulator with CEP stability and small temporal jitter in relation to electron bunches**
  - Formation of laser pulses with temporal shape modulation on THz frequency

Pulse shaping in IR region

To control the shape of laser pulses with a duration of ~30ps, it is necessary to provide:

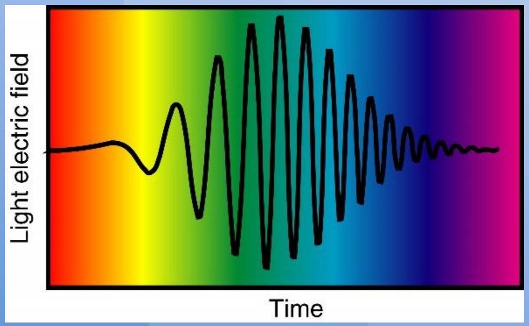
- **Broad spectral bandwidth (for λ=1030nm, Δλ ~ 8-10 nm)**
  (for formation sharp (0.1-1 ps) fronts in time domain + temporal diagnostic)

- **Linear frequency chirp**
  (temporal profiling due to manipulations with spectral amplitude. Spectron condition T>>T$_F$ lead to a linear relation between spectral and temporal shapes.

Spectron condition (T>>T$_F$)

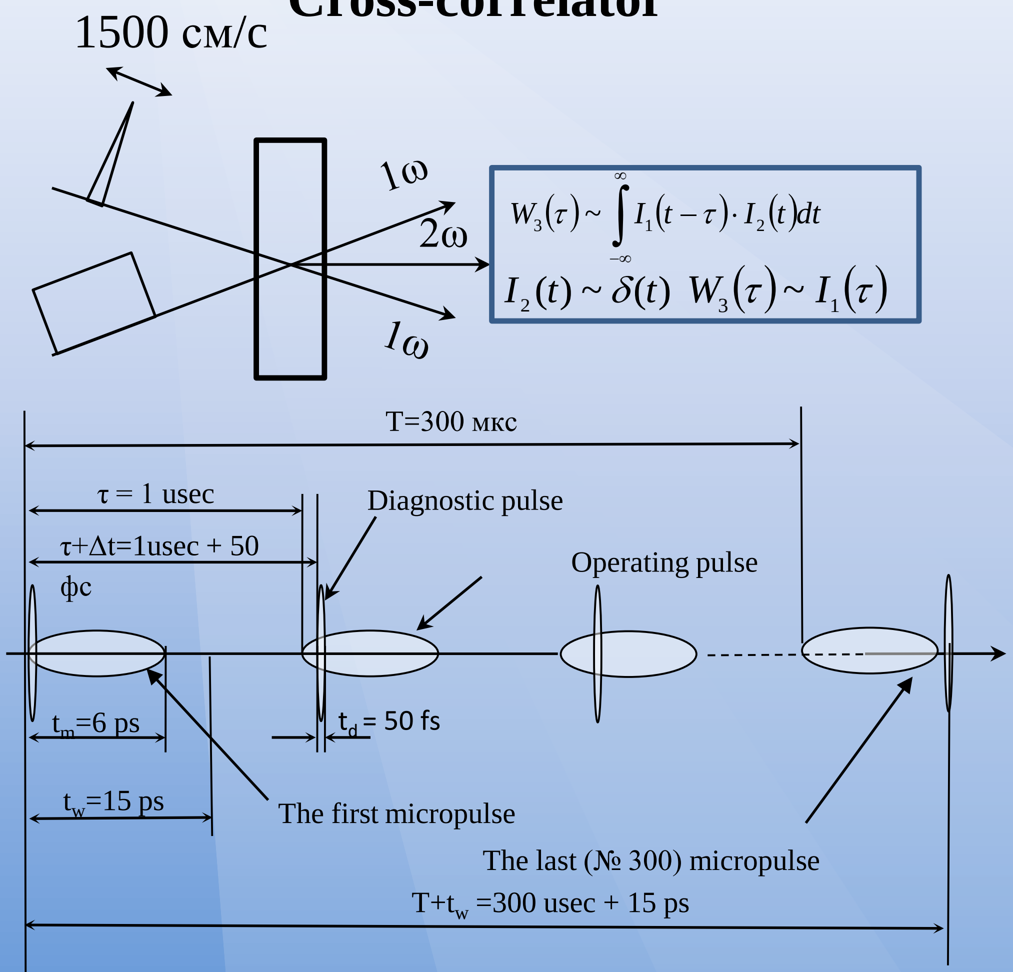
$$\left|A(t)\right|^2 \propto \left|S(\Omega)\right|^2 \quad \Omega \propto t$$

$$S_{req}(\Omega) = M(\Omega)\cdot S_{in}(\Omega) \xrightarrow{\text{FT}} A_{req}(t)$$

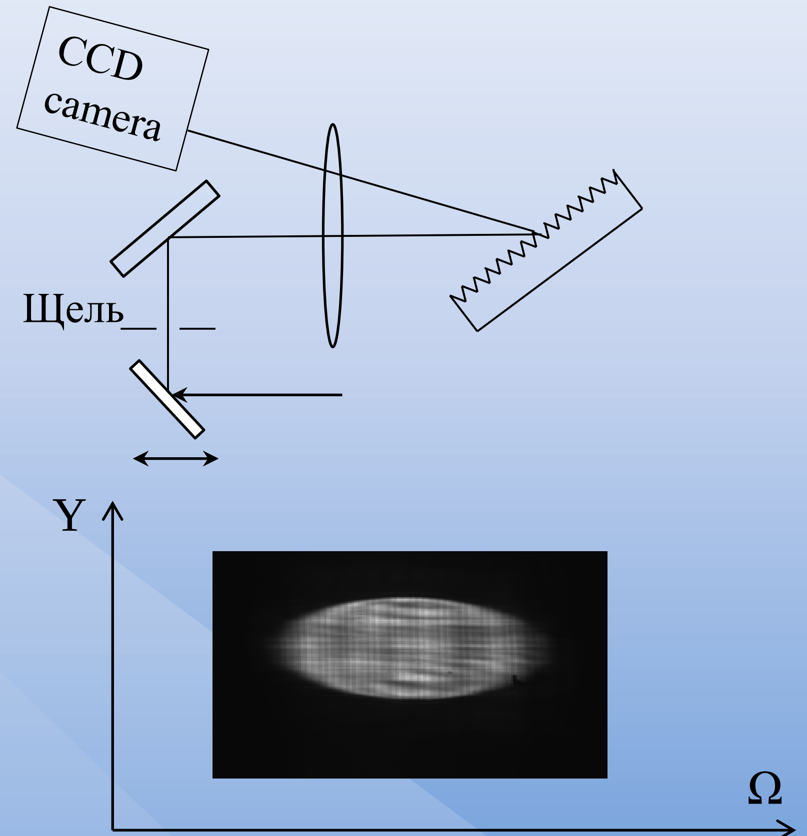


Methods of pulse diagnostic

Cross-correlator



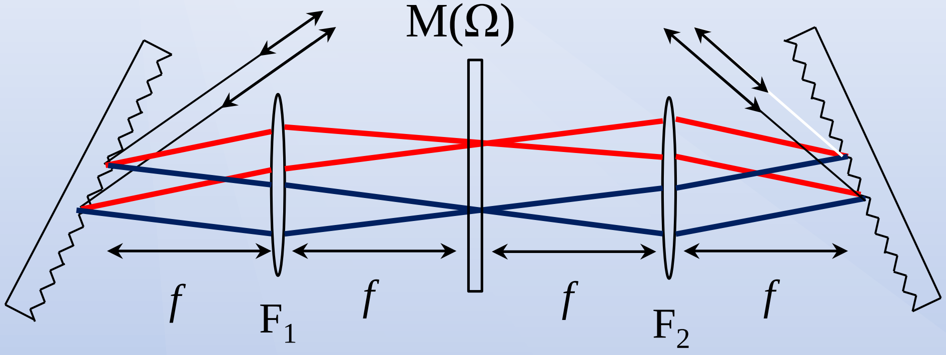
3D spectrograph

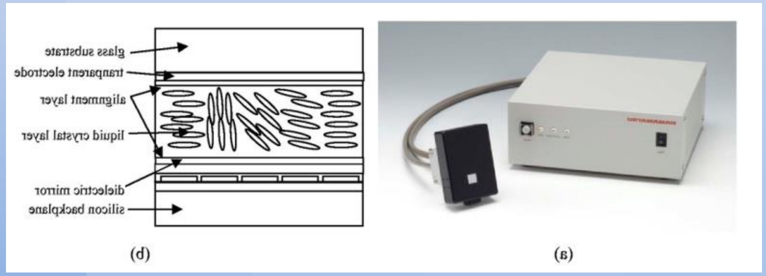


Зеленогорский В.В., Андрианов А.В., Гачева Е.И., Геликонов Г.В., Красильников М., Мартьянов М.А., Миронов С.Ю., Потемкин А.К., Сыресин Е.М., Штефан Ф., Хазанов Е.А. Сканирующий кросс-коррелятор для мониторинга однородных трехмерных эллипсоидальных лазерных пучков // Квантовая Электроника, v.44, №1, p.76-82, 2014.

Formation of 3D quasi-ellipsoidal pulses with help of Spatial Light Modulator

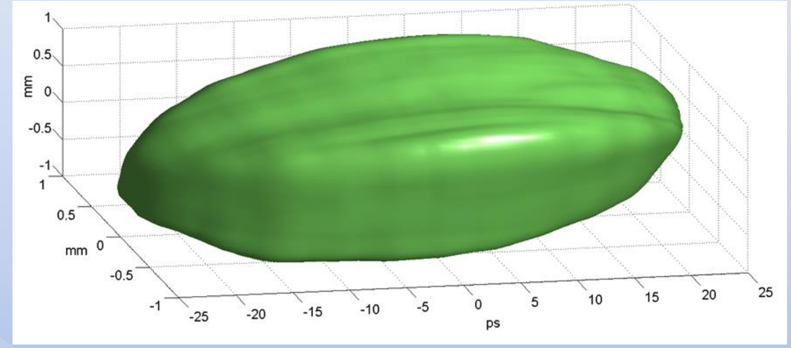
90° beam rotation



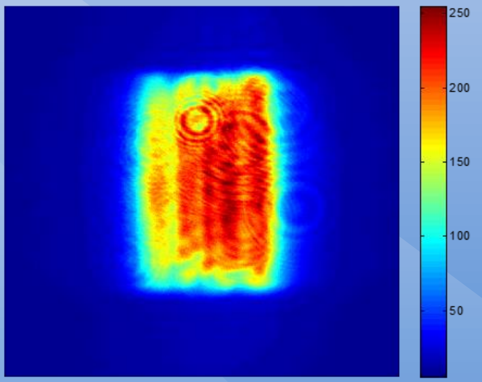


SLM+ polarizing elements

Experimental results (restored structure)



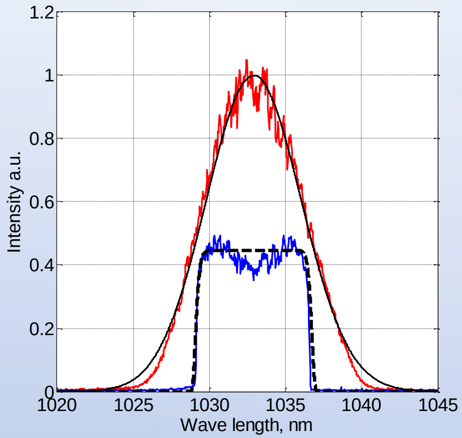
Nearfield (experimental result)

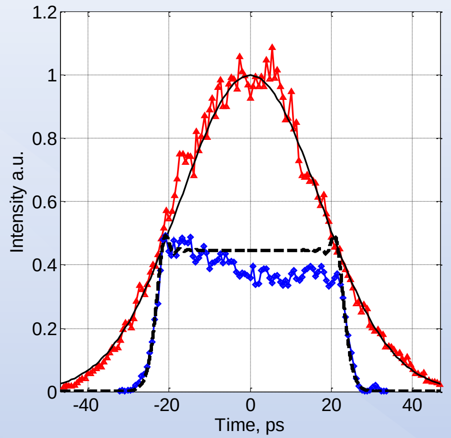


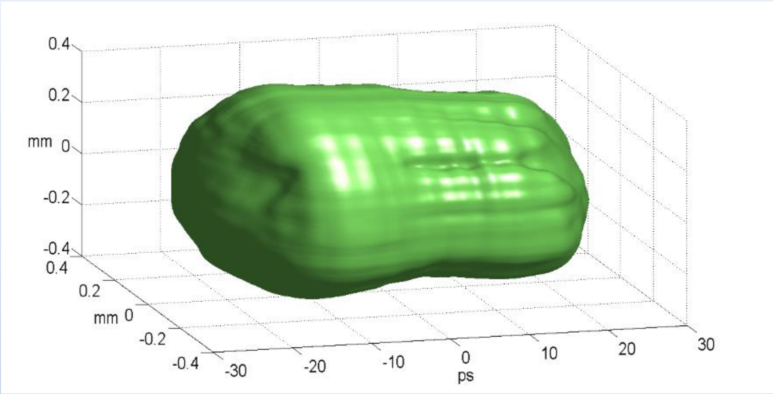
<u>Disadvantages:</u>

- There is no axial symmetry
- Astigmatism of cylindrical telescope

Formation of cylindrical pulses



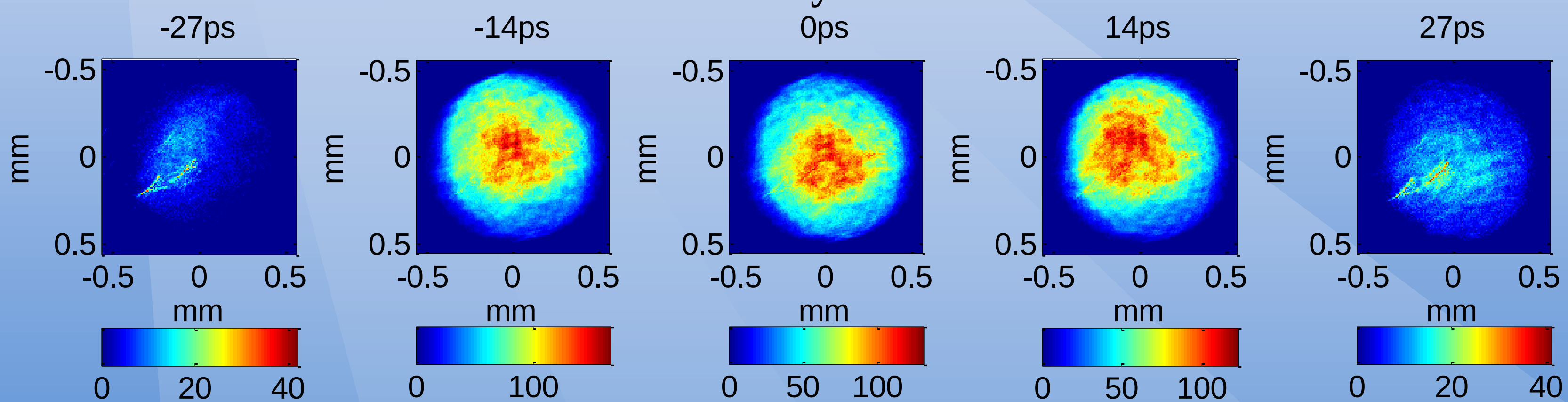




Pulse duration 41 ps

Pulse front: $\tau_F = 4\,ps$

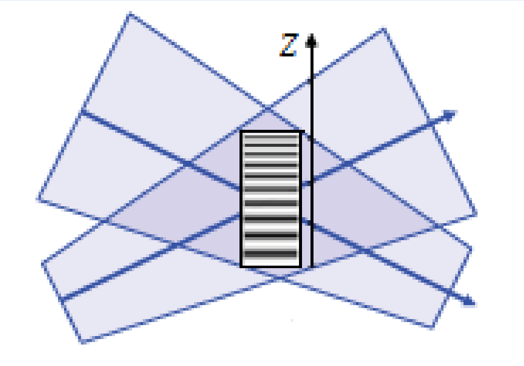
Transversal intensity distribution



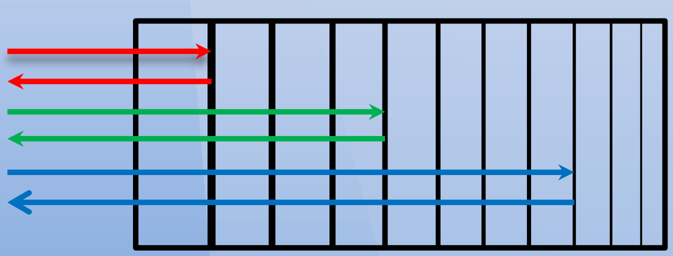
Mironov S.Y., Potemkin A.K., Gacheva E.I., Andrianov A.V., Zelenogorskii V.V., Krasilnikov M., Stephan F., Khazanov E.A. Shaping of cylindrical and 3D ellipsoidal beams for electron photoinjector laser drivers // Appl Opt, v.55, №7, p.1630-5, 2016

Formation of 3D ellipsoidal laser pulses with help of 3D profiled CBG

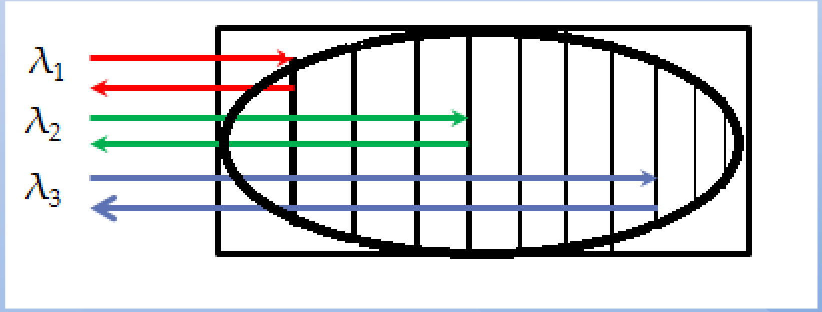
Material:
Photo-thermo-refractive glass
Writing technology:
Interference of diverging and converging laser beams
Actual for 800nm-2500 nm wavelengths



Commonly used VBG

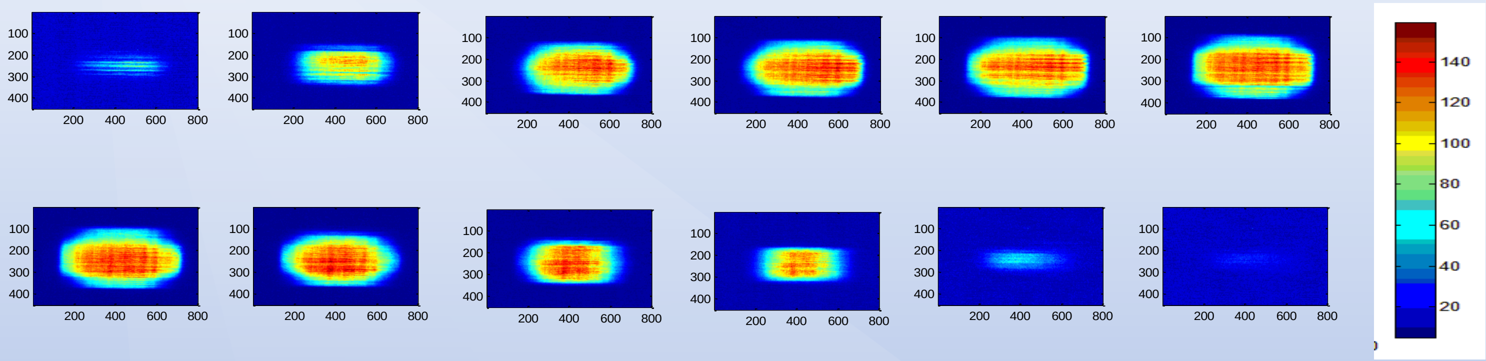


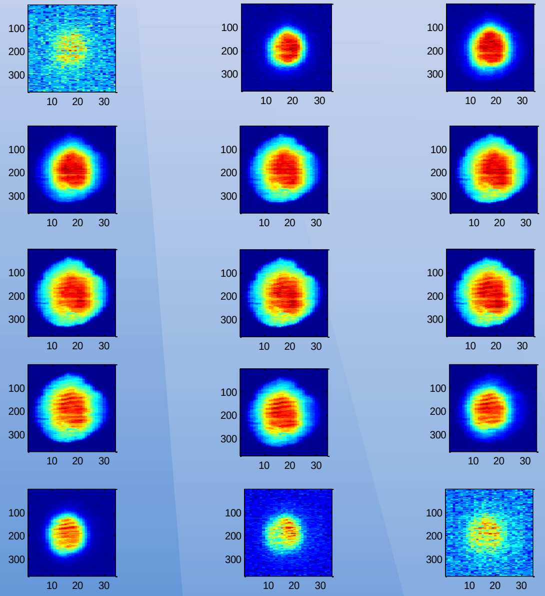
Profiled CBG



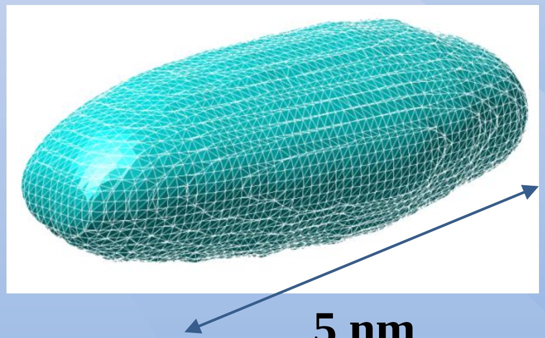
Method of 3D ellipsoid formation:
Formation of cylindrical laser pulse and reflection from 3D CBG

Formation of quasi-cylindrical pulses with help of 3d CBG



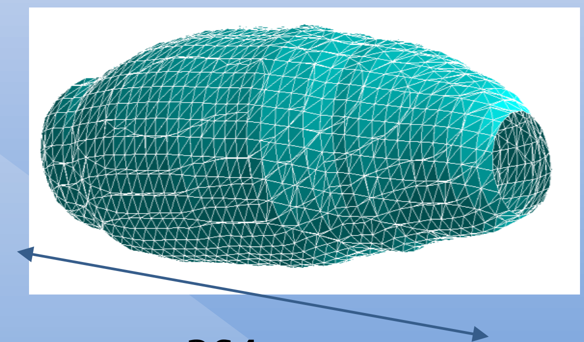


Spectrograph



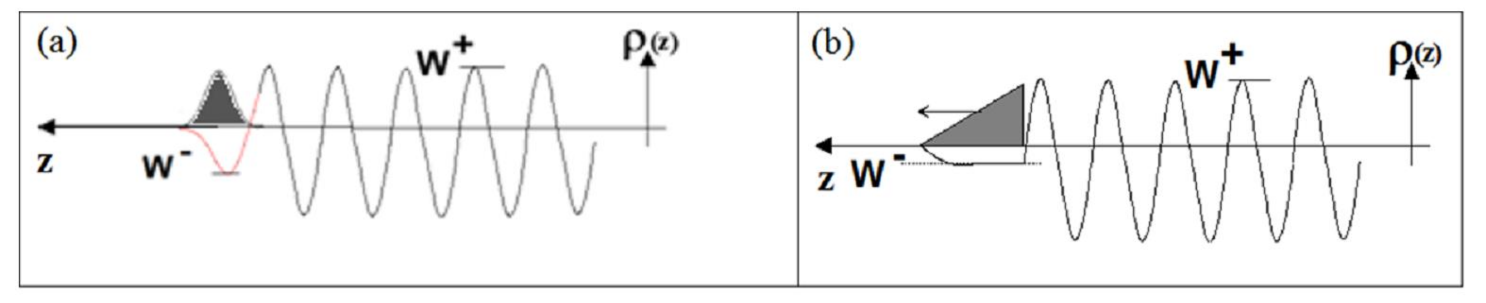
5 nm

Cross-correlator



264 ps

Formation of triangular laser pulses

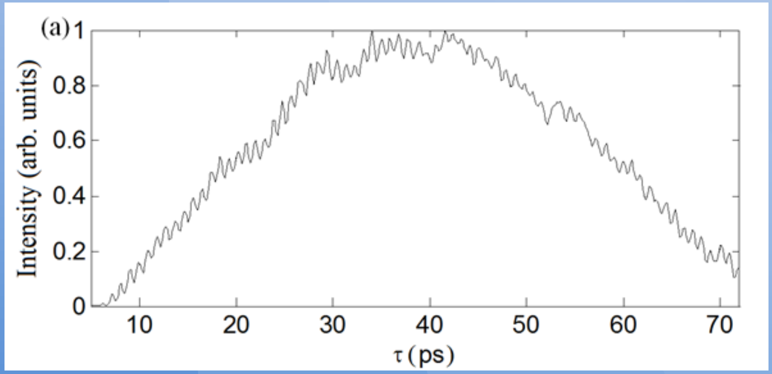


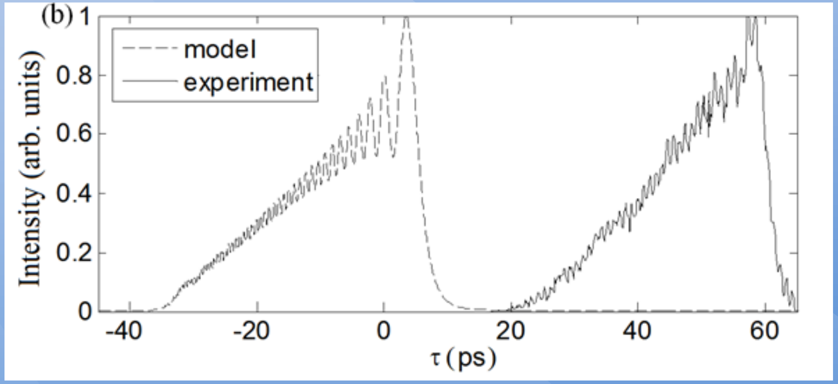
$TR = \frac{|W^+|}{|W^-|}$ $W^{+(-)}$ amplitude of electric field (inside) electron bunch

TR – characterize maximum energy transfer ratio at accelerating process

The more TR, the less charge of "drive" beam is required and smaller accelerating length for "witness" bunch

For symmetrical charge distributions TR<2 –> it is necessary to destroy symmetry. Formation of a bunches with triangular space charge distribution is a solution





Formation laser pulses with a periodic modulation (in time domain) on THz frequency

Periodic modulation in laser pulse will transferred to modulation of space charge distribution. It helps to:

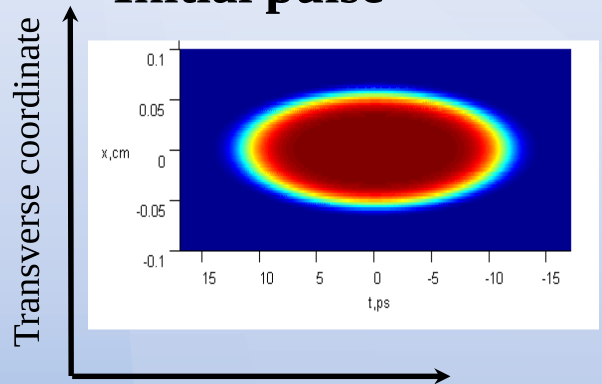
- Generate THz radiation in undulator not from a fluctuation noise
- Generate THz radiation with CEP stability and low temporal jitter in relation to electron bunches. It is important for pump-and probe experiments, where THz radiation is a pump and electron bunch is a probe.

Methods of a periodic modulation formation
(pulse duration ~30 ps, typical period ~ 1-5 ps)

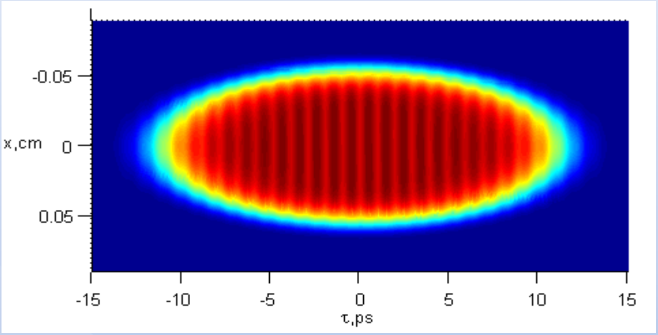
- Introducing of sinusoidal spectral phase to laser pulses with help of SLM
- An usage of different type interferometers to introduce time delay between linearly chirped replicas. The delay leads to beating between different frequencies and is a reason of formation a modulation in temporal profile.

Harmonic modulation of the spectral phase for linearly chirped laser pulses

Initial pulse



Modulated pulse



$$E(t) = \int A(\omega)\exp\left(i\alpha\omega^2/2\right)\exp\left(ih\cos\omega T\right)\exp\left(i\omega t\right)d\omega$$

$$E(t) = J_0(h)E_0(t) + \sum_{n=1}^{\infty} i^n J_n(h)\left(E_0(t-nT)+E_0(t+nT)\right)$$

Field amplitude: E(x,y,t)

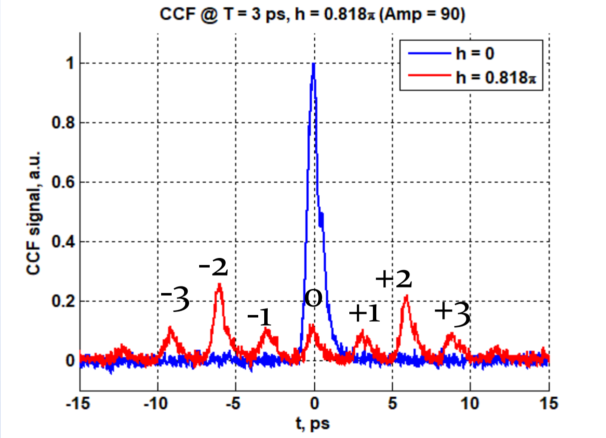
Initial spectrum: $A(x,y,\omega)\cdot e^{i\cdot\frac{\alpha\cdot\omega^2}{2}}$

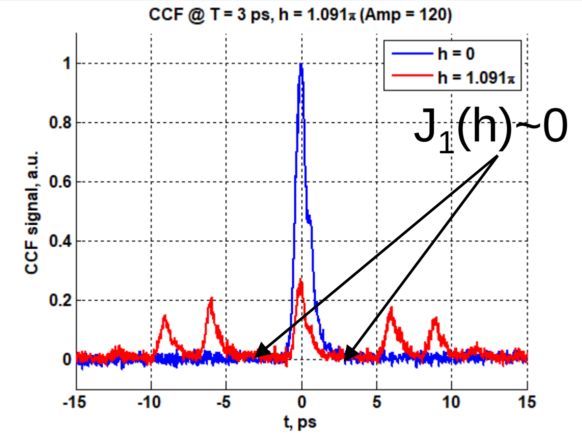
α, h and T are free parameters. Control of the parameters makes possible to generate separated replicas in time and produce periodic modulation.

Physically the produced modulation is a result of interference between replicas.

Experimental results

FTL pulse + introducing of a harmonic spectral phase

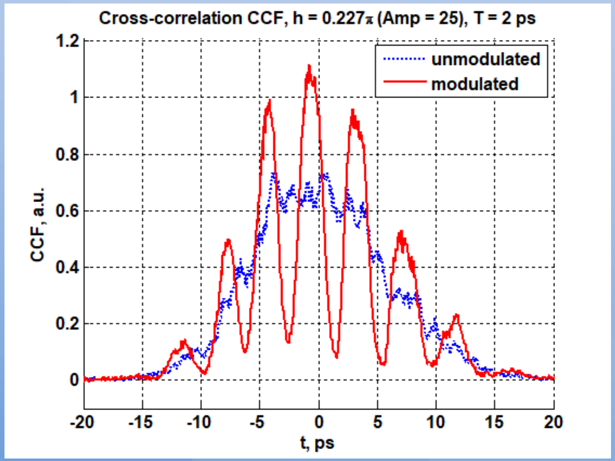


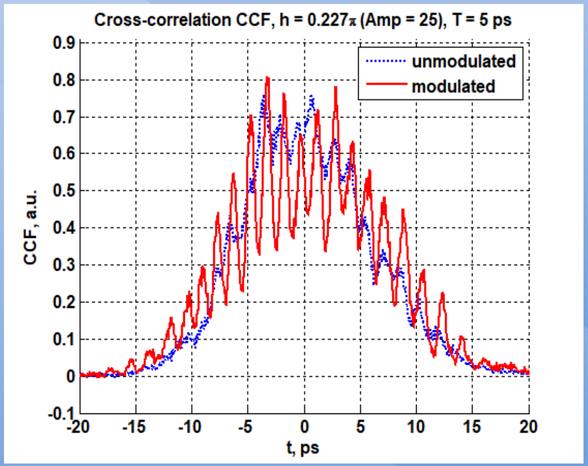


Chirped pulse + introducing of a harmonic spectral phase

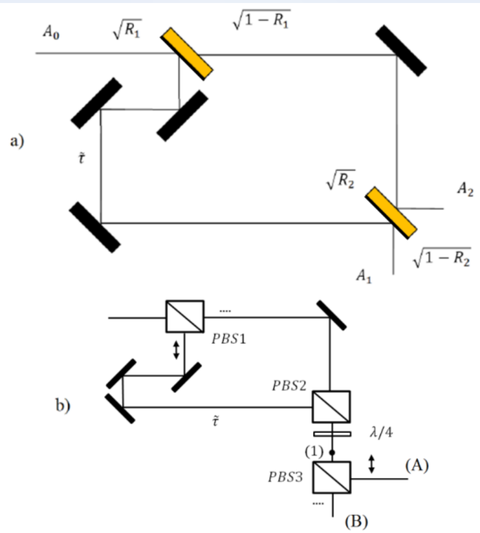
ν=0.26 THz

ν= 0.66 THz





Using of Mach-Zehnder interferometer for producing periodically modulated pulses



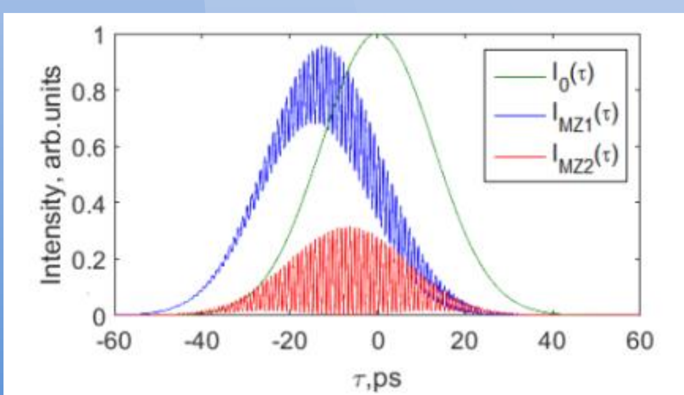
Key parameters:

- Mirror reflection coefficients R_1,R_2
- Time delay
- Spectral bandwidth, duration and chirp

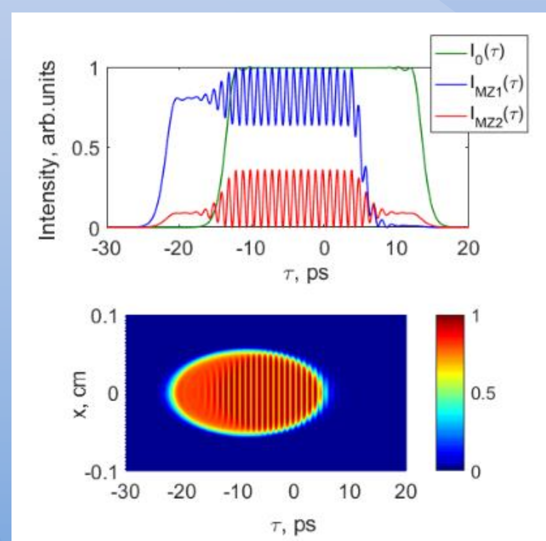
Pecularitites:

- The scheme works properly for Gaussian beams
- There is a difficulty if the pulses has a sharp fronts (there is no field – there is no interference)
- The idea can be applicable for IR,VS, UV pulses

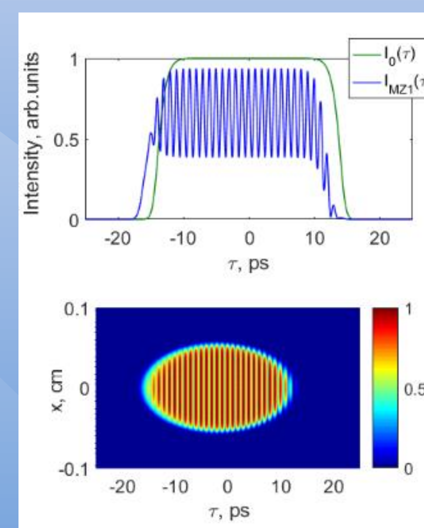
$R1$= 0.9,$R2$= 0.9,T=1ps $\Delta\lambda = 8$ nm



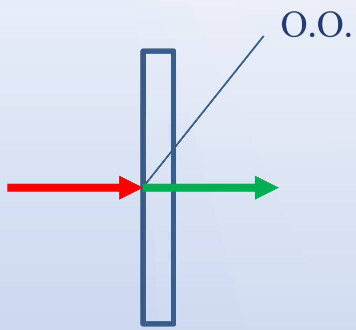
$R1$= 0.9,$R2$= 0.9, T=1ps, $\Delta\lambda = 8$ nm



$R1$= 0.9,$R2$= 0.7, $\Delta\lambda = 50$ nm, T=1 ps



Retaining of pulse shapes at harmonic generation stage



Efficiency and shape retaining are determined by:

- A relation between NC thickness and a nonlinear length
- Impact of walk-off effect
- Phase matching conditions for the spectral bandwidth

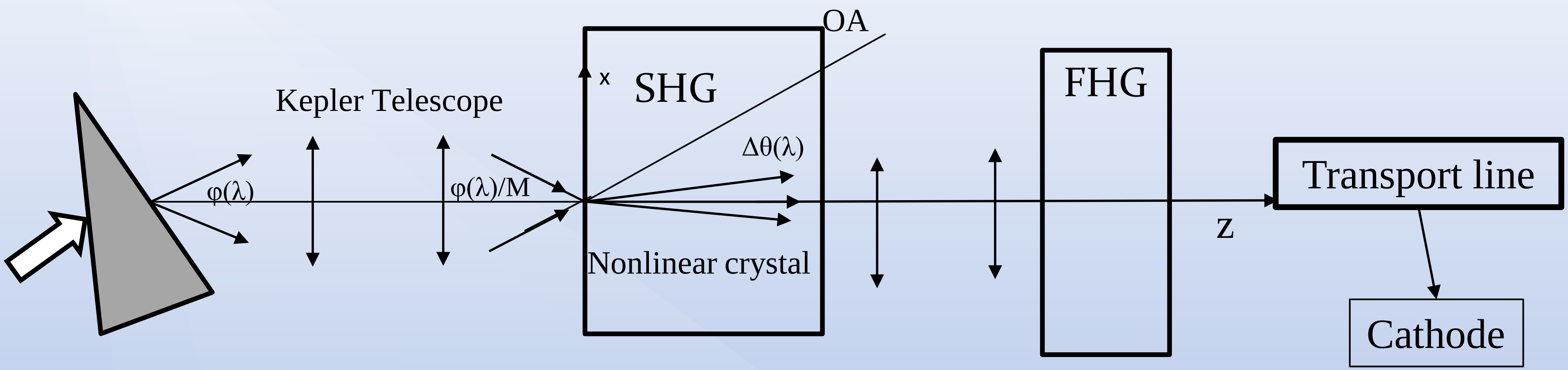
$$A_2 \sim -i \cdot \beta \cdot A_1^2 \cdot e^{-i \cdot \Delta k \cdot L}$$

$$\boxed{\Delta k(\Omega) = k_{1z} + k_{1z} - k_{2z} \neq 0}$$

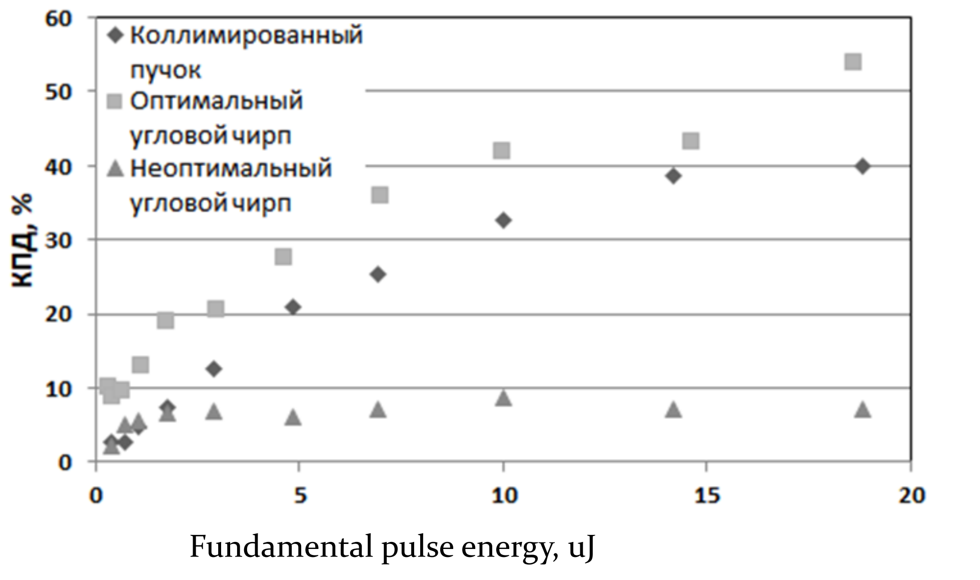
Minimization of phase mismatching is possible if:

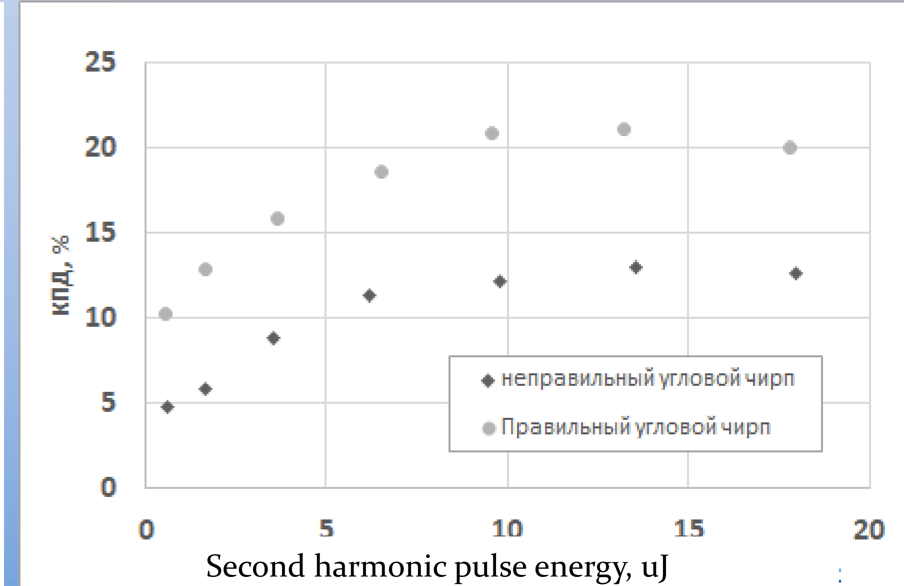
- **Use crystals with smaller thickness (to keep efficiency, it is necessary to simultaneously increase peak intensity)**
- **Satisfy phase matching conditions for each frequency (produce angular chirping)**
- **Squeeze spectral bandwidth of SH pulses (It can be done if the process is non-collinear and pulses have opposite chirps)**

Angular chirping at SHG and FHG processes



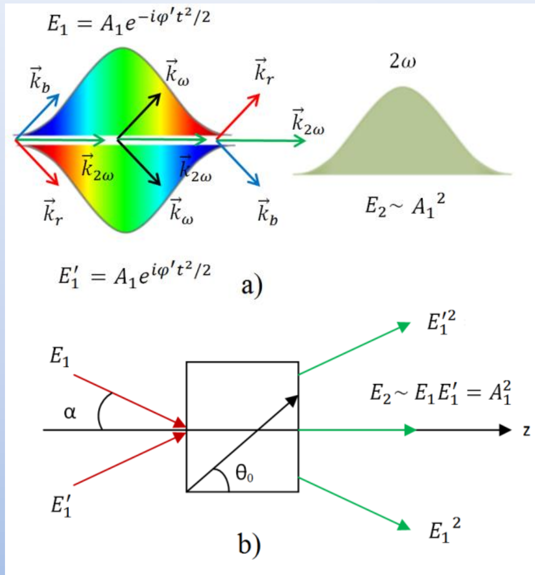
Each spectral component is directed to NC at its optimal phase matching angle for SHG and FHG processes

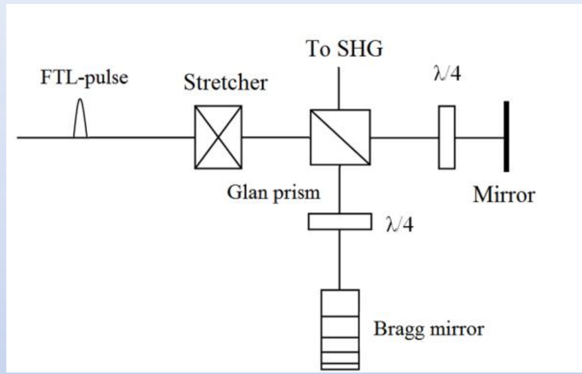


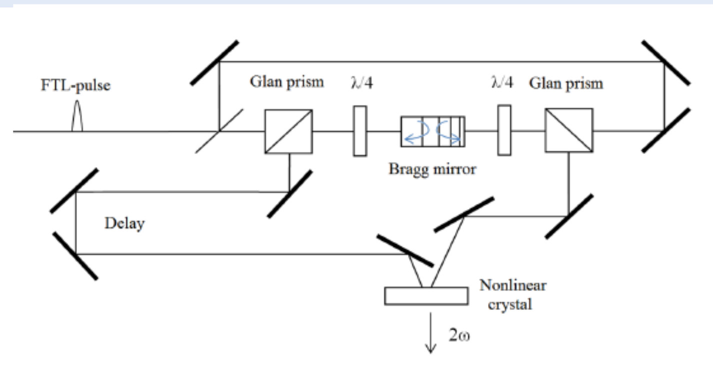


High efficiency SHG at interaction laser pulses with opposite frequency chirps

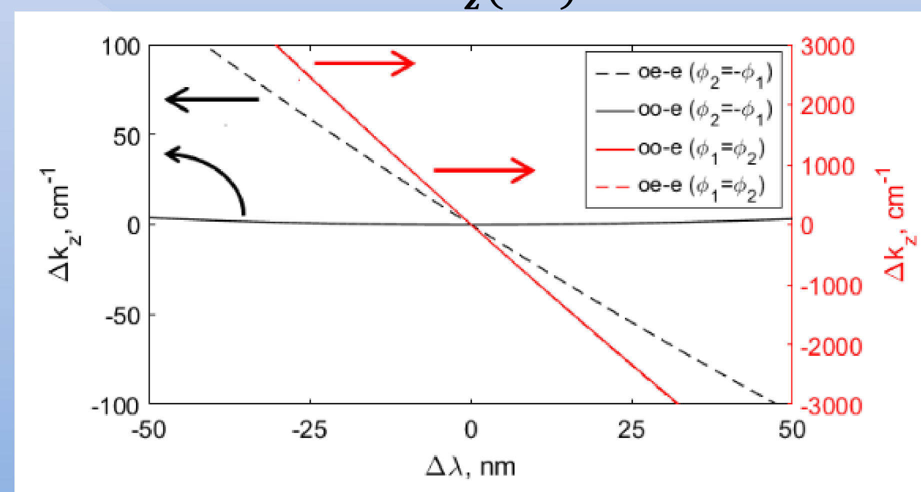
Possible realization:







$\Delta k_z(\Delta\lambda)$



Phase matching:

$$\Delta k_z(\Omega) = k_{1z}(\omega_{10} + \Omega) + k_{1z}(\omega_{10} - \Omega) - k_{2z}(\omega_{20})$$

oo-e interaction

$$\Delta k_z(\Omega) = \beta_2 \Omega^2 + 2\sum_{n=2}^{N} \frac{\beta_{2n}}{(2n)!}\Omega^{2n},$$

eo-e interaction

$$\Delta k_z(\Omega) = (\beta_1{}^o - \beta_1{}^e)\Omega + \frac{1}{2}\left[\beta_2{}^o + \beta_2{}^e\right]\Omega^2 + \sum_{n=3}^{N} \frac{\beta_n{}^o + (-1)^n \beta_n{}^e}{n!}\Omega^n$$

Initial boundary conditions:

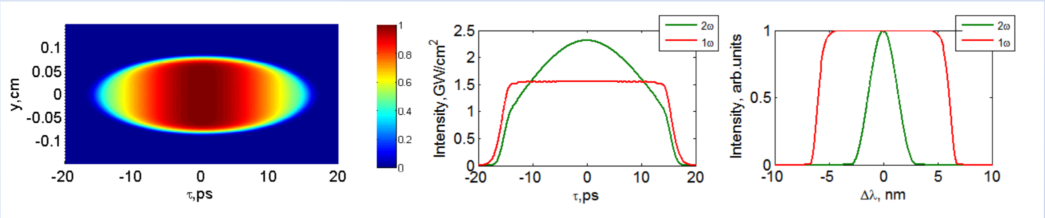
$$\tilde{A}_1\left(x,y,\Omega,z=0\right) = A_{01} e^{-\cosh\left(\left[\left(\frac{2\Omega}{\Delta\omega}\right)^2+\left(\frac{2x}{\Delta x}\right)^2+\left(\frac{2y}{\Delta y}\right)^2\right]^4\right)} \cdot e^{-i\Omega\cdot y\cdot\frac{tg(\alpha)}{v_z}} e^{-i\varphi_1\frac{\Omega^2}{2}} e^{iA_0\cos(\Omega T+\varphi_0)}$$

$$\tilde{A}_2\left(x,y\Omega,z=0\right) = A_{02} e^{-\cosh\left(\left[\left(\frac{2\Omega}{\Delta\omega}\right)^2+\left(\frac{2x}{\Delta x}\right)^2+\left(\frac{2y}{\Delta y}\right)^2\right]^4\right)} \cdot e^{i\Omega\cdot y\cdot\frac{tg(\alpha)}{v_z}} e^{-i\varphi_2\frac{\Omega^2}{2}} e^{iA_0\cos(\Omega T+\varphi_0)}$$

SHG: Nonlinear crystal BBO thickness 1.5 мм.
Central wavelength 1034 nm.
Pulse duration 30 ps

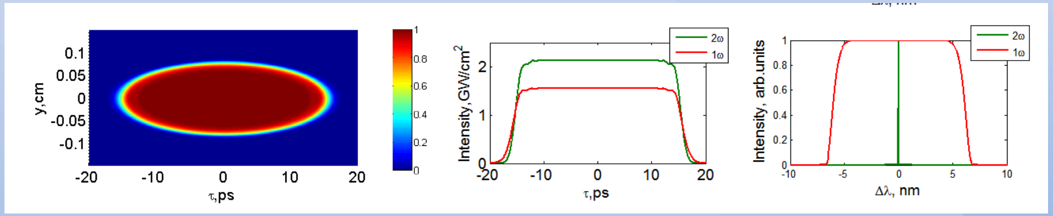
Second harmonic generation

$\varphi_1 = \varphi_2$



Spectral bandwidth (FWHM) 12 nm

$\varphi_2 = -\varphi_1$



Spectral bandwidth (FWHM) 12 nm

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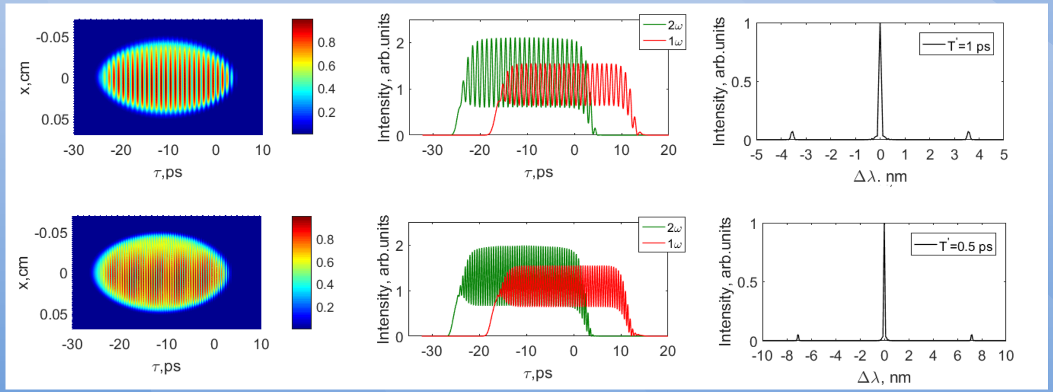

Spectral bandwidth (FWHM) 50 nm, modulation period 1 ps

Spectral bandwidth (FWHM) 75 nm, modulation period 0.5ps

Possible applications of photoinjector in IAP RAS

- Generation of electron bunches (q ~0.1 nC, W~3MeV) and tasks devoted to minimization of normalized emittance. Additional acceleration of electron bunches up to ~20MeV in accelerating sections
- Experiments on generation of far UV, X-ray and γ-radiation by backward Compton scattering of laser pulses on accelerated electron beams
- Generation of (1-10) THz radiation in an undulator, as well as in direct Compton scattering by electrons due to a decrease in the energy of scattered photons
- Wakefield acceleration of electron bunches up to GeV energies in plasma created by PW laser pulse

Спасибо за внимание!