Accelerators based compact sources of quasi-monochromatic radiation for phase-contrast X-ray imaging

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Participation of IAP in LIA IDEATE

Institute of Applied Physics

National Academy of Sciences of Ukraine

(Sumy, Ukraine)

The LIA IDEATE covers R&D and optimisation of innovative technologies for the experiments at the particle accelerators and development of accelerator techniques.

Research program and projects

- R&D of detector technologies
- Accelerator techniques
- Experimental platforms
- R&D on instrumentation for medical applications
- Developments for flavour physics
- Developments for nuclear physics
- Developments for hadron physics
- Pedagogical activities

Phase-contrast X-ray imaging

Phase-contrast X-ray imaging

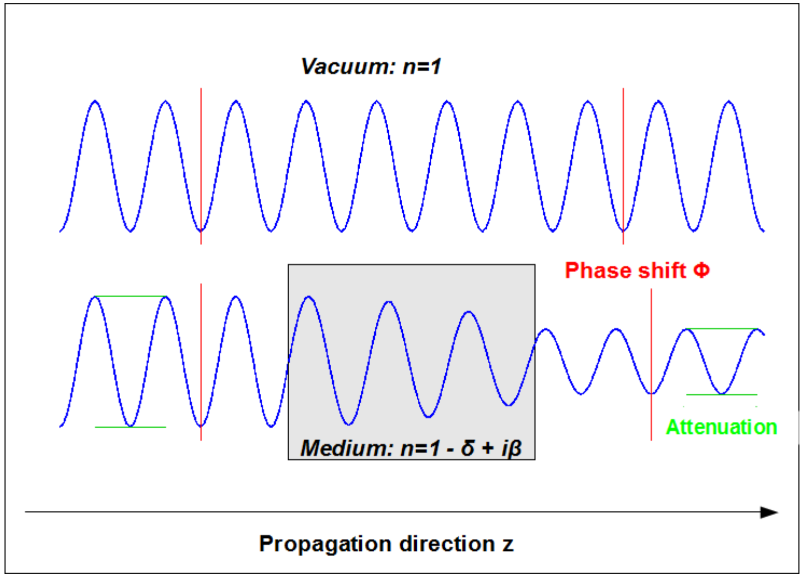
Phase-contrast X-ray imaging (PCI) is a general term for different technical methods that use information concerning changes in the phase of an X-ray beam that passes through an object in order to create its images.

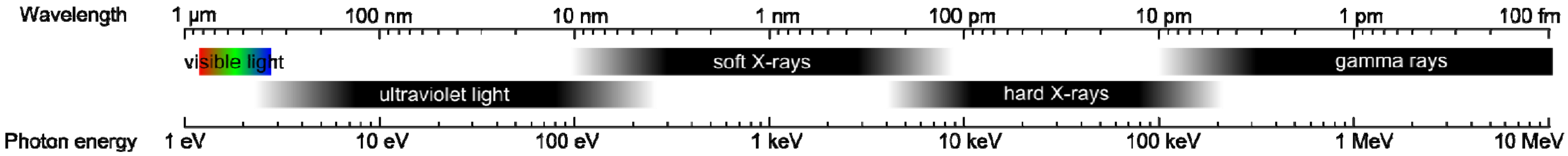
$$\Psi(z) = E_0 e^{inkz} = E_0 e^{i(1-\delta)kz} e^{-\beta kz}$$

the phase shift

an exponential decay factor decreasing the amplitude of the wave

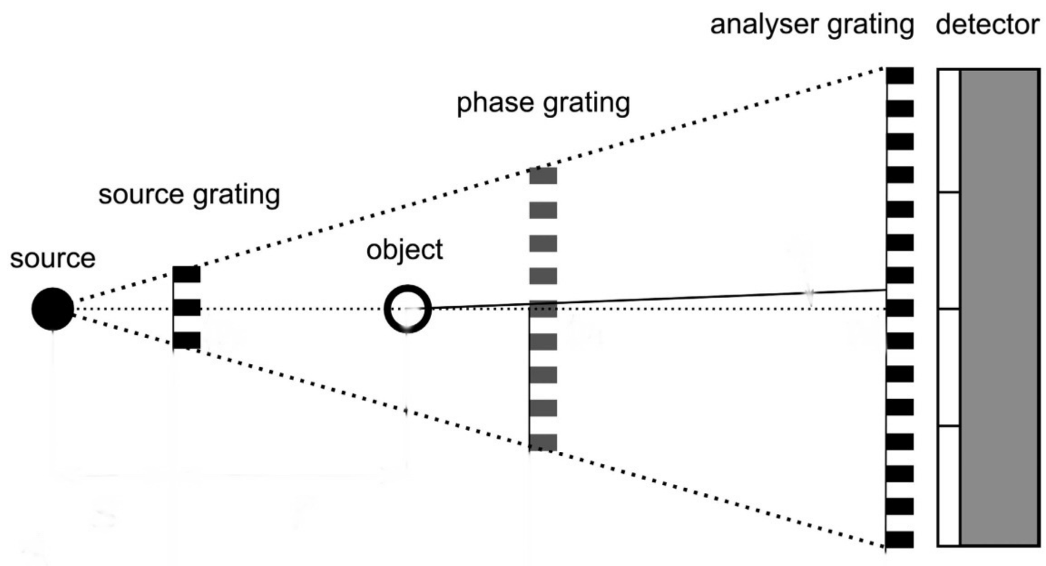
$$\delta \propto k^{-2} \qquad \beta \propto k^{-4}$$





Phase-contrast X-ray imaging.
Experimental realisation

- Crystal interferometry
- Grating Bonse-Hart
- Analyzer-based imaging
- Propagation-based imaging
- Edge-illumination
- Grating-based imaging (Talbot interferometry)

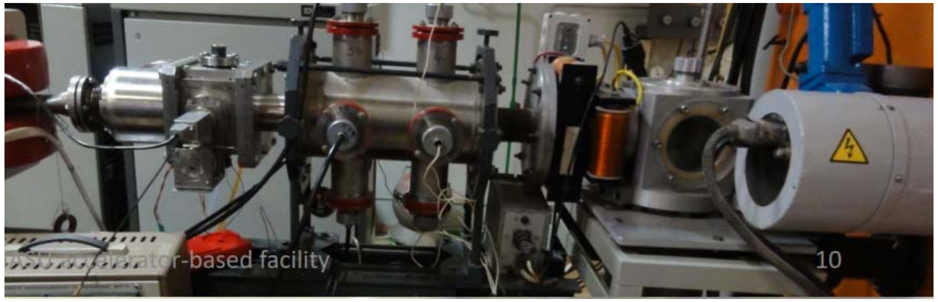


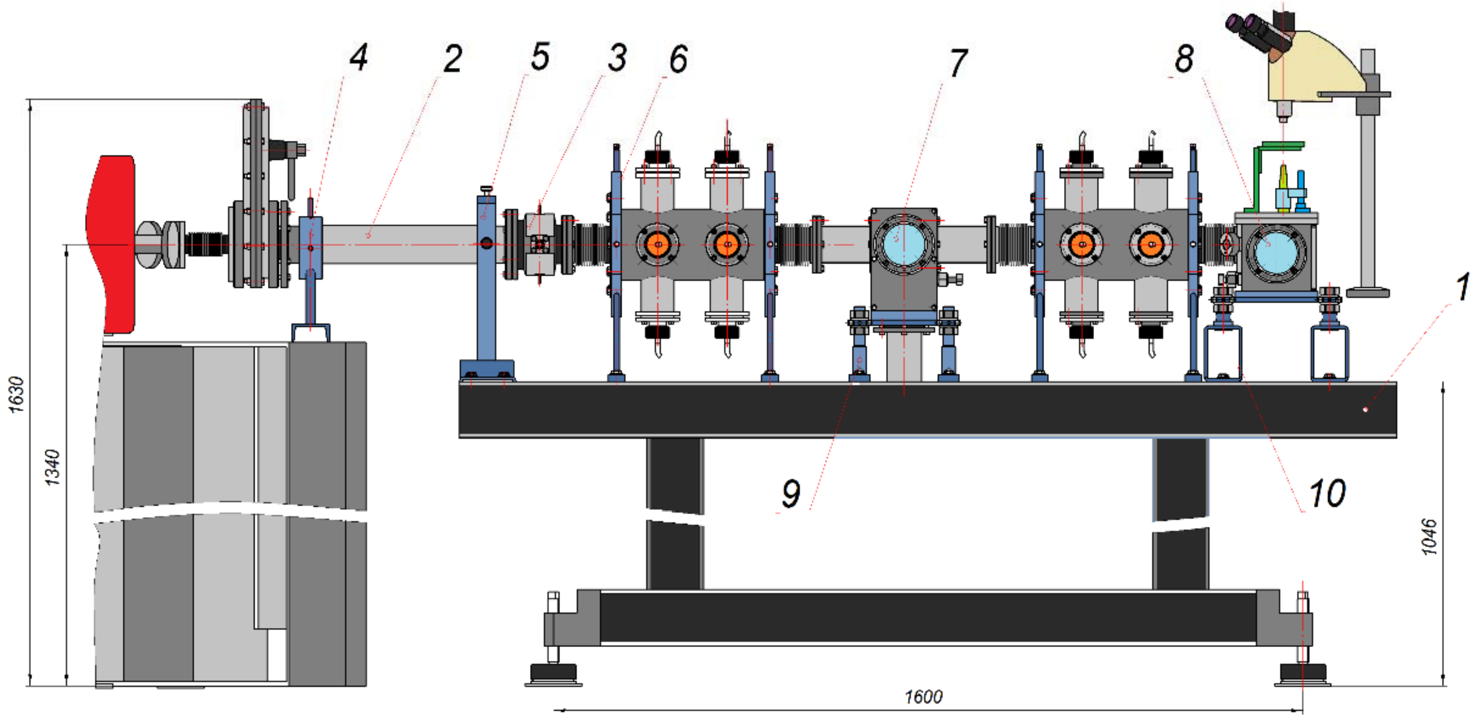
Required characteristic of radiation for X-ray phase contrast

Energy range	ΔE/E	Source size	Size on the object	Flux on the object	Coherence
> 10 keV	3%	small	50 cm	> 10^(9) ph/s	yes

Accelerators based compact source of quasi-monochromatic X-ray at IAP NASU

3D model and a general view of the quasimonochromatic X-ray source with ion excitation.

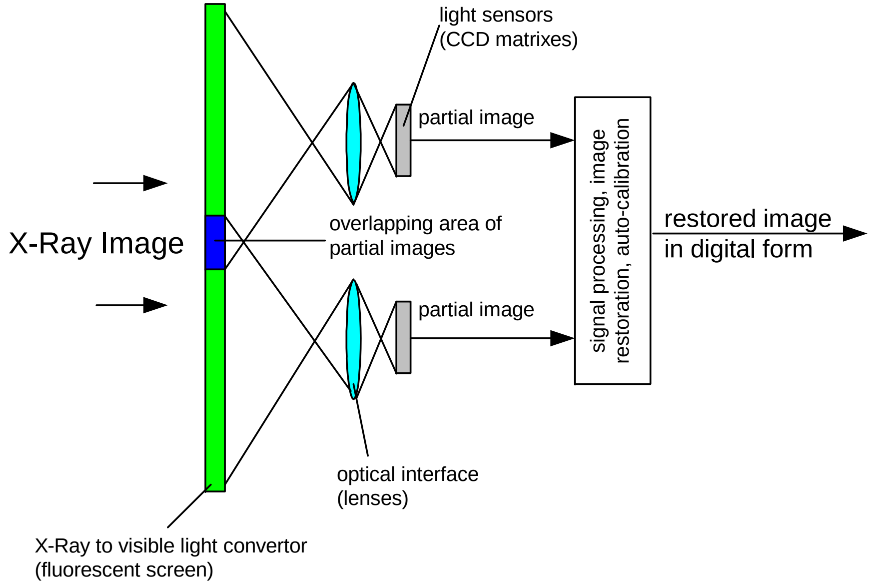




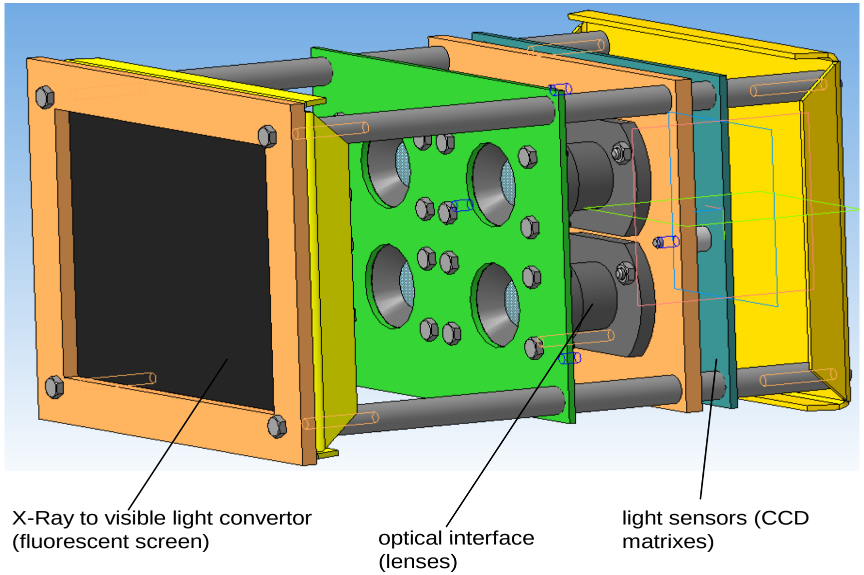
Multimatrix X-Ray detector
for phase contrast imaging experiments

Basic parameters

Sensitive Area	90x60mm
Optical Configuration	2x2 cells
DQE(0)	0.44
Optical Resolution	up to 12 pl/mm
Dynamic Range	equal to 14bits
Energy of detected X-Ray quantum	9-100keV (for different conversional screens)
Frame rate	15-150 FPS
External digital interface	Gigabit Ethernet



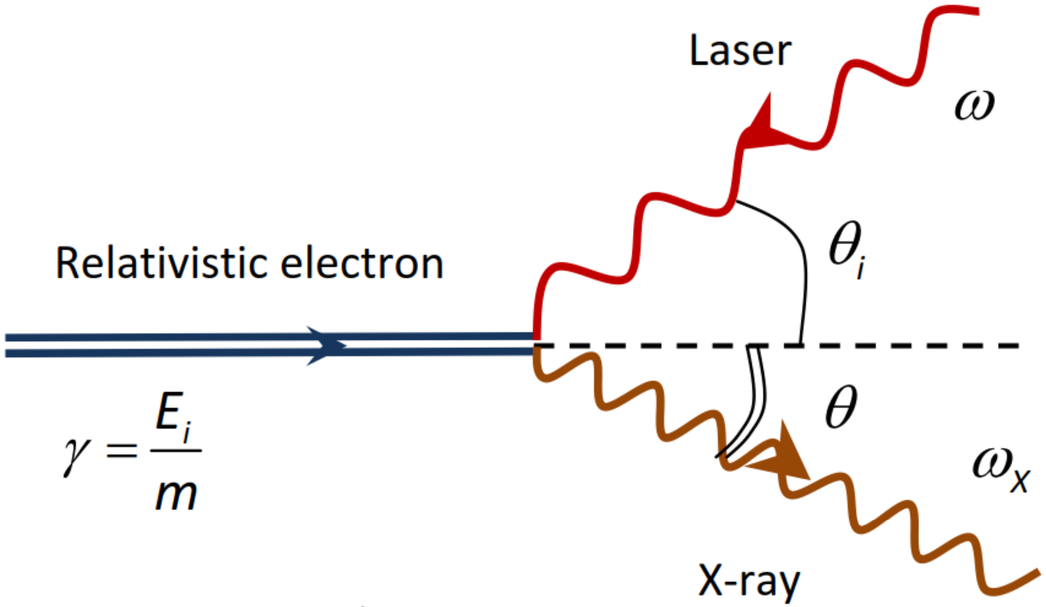
Optical scheme of the detector



3D CAD Driwing of the Multimatrix Hybrid X-Ray Detector

Photo of the Multimatrix Hybrid X-Ray Detector

Compton backscattering process



$$\gamma = \frac{E_i}{m}$$

$$\gamma \gg 1 \Rightarrow \theta \sim 1/\gamma$$

Energy of X-ray photons, which are emitted by a relativistic electron in collision with the laser pulse

$$\hbar\omega_X \approx \hbar\omega \frac{2\gamma^2 (1 + \cos\theta_i)}{1 + \gamma^2\theta^2}$$

X-ray sources based on Compton backscattering

	Type	Energy [KeV]	Flux (@ 10% bandwidth)	Source size (μm)
*PLEIADES (LLNL) [11,12]	Linac	10-100	10^7 (10 Hz)	18
*Vanderbilt [13,14]	Linac	15-50	10^8 (few Hz)	30
*SLAC [15]	Linac	20-85		
*Waseda University [16,17]	Linac	0.25-0.5	2.5 10^4 (5 Hz)	
*AIST, Japan [18]	Linac	10-40	10^6	30
*Tsinguha University [19]	Linac	4.6	1.7 10^4	
*LUCX (KEK) [20]	Linac	33	5 10^4 (12.5 Hz)	80
+ UTNL, Japan [21,22]	Linac	10-40	10^9	
MIT project [23]	Linac	3-30	3 10^{12} (100 MHz)	2
MXI systems [24]	Linac	8-100	10^9 (10Hz)	
SPARC –PLASMONX [25]	Linac	20-380	2 10^8 -2 10^{10}	0.5-13
Quantum Beam (KEK) [26,27]	Linac		10^{13}	3
*TERAS (AIST) [28]	Storage ring	1-40	5 10^4	2
*Lyncean Tech [29,30,31]	Storage ring	7-35	~ 10^{12}	30
Kharkov (SNC KIPT) [32]	Storage ring	10-500	2.6 10^{13} (25 MHz)	35
TTX (THU China) [33,34]	Storage ring	20-80	2 10^{12}	35
ThomX France [35]	Storage ring	50	10^{13} (25 MHz)	70

ThomX - Conceptual Design Report

The spectral line broadening

Estimation of spectral line broadening for the parameters of ThomX source

$$\omega_{x0} = \omega \frac{2\gamma^2(1+\cos\theta_i)}{1+\gamma^2\theta^2}$$

Electron energy dispersion $\Delta\gamma/\gamma \sim 0.6\%$

$$\omega_x(\gamma) \approx \omega \frac{2(\gamma+\Delta\gamma)^2(1+\cos\theta_i)}{1+\gamma^2\theta^2} = \omega_{x0}\left(1+\frac{2\Delta\gamma}{\gamma}\right) \Rightarrow \frac{\Delta\omega_x(\gamma)}{\omega_{x0}} = \frac{2\Delta\gamma}{\gamma} \sim 10^{-3}$$

Spectral width of pulsed laser $\Delta\omega/\omega = 2\pi/\omega\tau \approx 0.35\%$

$$\omega_x(\omega) \approx \omega_{x0}\left(1+\frac{\Delta\omega}{\omega}\right) \Rightarrow \frac{\Delta\omega_x(\omega)}{\omega_{x0}} = \frac{\Delta\omega}{\omega} \sim 10^{-3}$$

$$\boxed{\frac{\Delta\omega_x(\gamma)}{\omega_{x0}} \sim \frac{\Delta\omega_x(\omega)}{\omega_{x0}}}$$

The same energy width corresponds of X-ray emission angle $\theta \sim 1$ mrad

$$\frac{\Delta\omega_x}{\omega_x} = \sqrt{\left(\frac{2\Delta\gamma}{\gamma}\right)^2 + \left(\Delta\theta_i \tan\frac{\theta_i}{2}\right)^2 + \left(\frac{\Delta\omega}{\omega}\right)^2 + Nonlinear\_Effects}$$

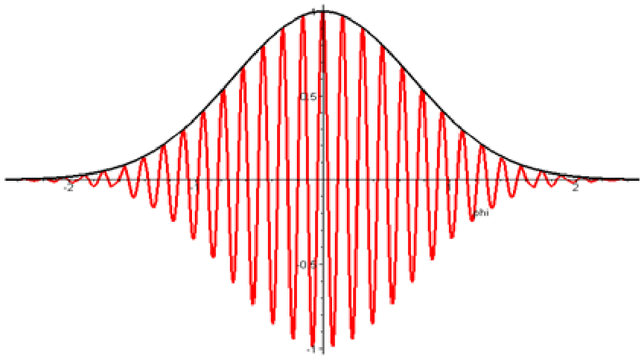
Compton backscattering process. Accounting of a pulse character of the laser field

Conservation law $p_i + \hbar k = p_f + \hbar k_X$

Four-potential of pulsed laser wave

$$A^{\mu}_{pul}(\varphi) = g\left(\frac{\varphi}{\omega\tau}\right) A^{\mu}_{mon}(\varphi)$$

Quasi-monochromatic condition $N_{pul} = \frac{\omega\tau}{2\pi} \gg 1$



Here φ is the laser-wave phase, $A^{\mu}_{mon}(\varphi)$ is four-potential of plane monochromatic wave, the function $g(\varphi/\omega\tau)$ is envelope function of the four-potential of an external wave, that allows us to take into account the pulsed character of a laser field.

Klein -Nishina formula can be summarized in the case, when an external laser field has a pulsed character. The energy of X-ray photon has a finite spectral width even at the fixed emission angle. The differential probability of one-photon Compton backscattering :

$$\frac{dW}{dW_{KN}} = N_{pul} \frac{\tau}{\tau_e} \int_0^{\tau_e/\tau} d\xi \cdot g(\xi) \int_{-\infty}^{\infty} d\xi' \cdot g(\xi') \cos\left(\tau\left(\omega_x + E_f - E_i - \omega\right)(\xi' - \xi)\right)$$

Compton backscattering process. Accounting of a pulse character of the laser field

For the ThomX project typical laser parameters are: $\hbar\omega = 1.23$ eV, $\tau = 1$ ps, and the electron beam parameters are: $E_i = 50$ MeV ($\gamma \approx 100$), $\tau_e = 20$ ps.

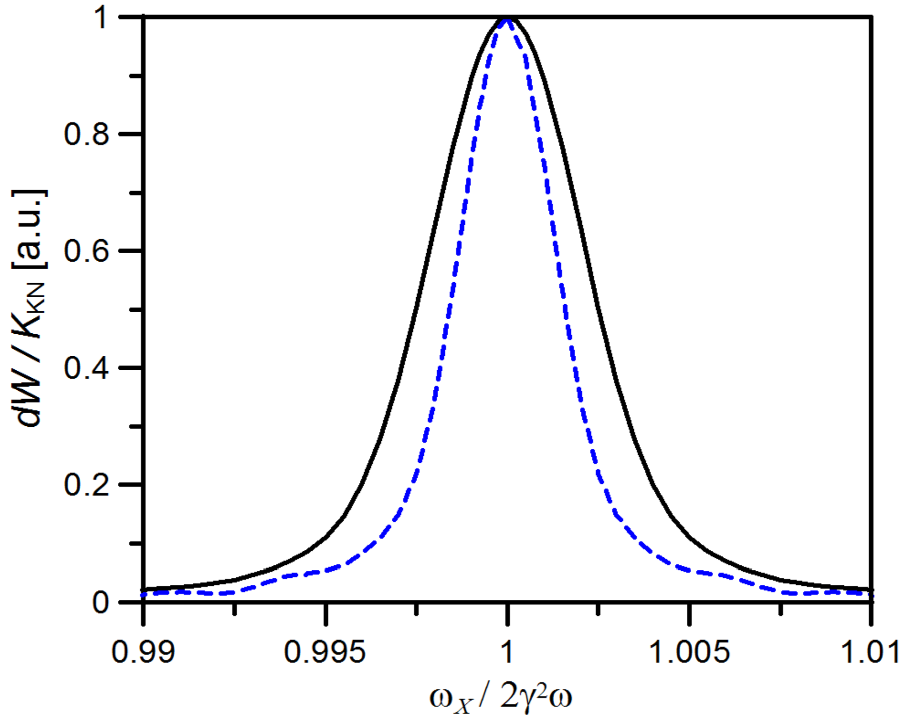


Figure. Broadening of X-ray spectrum caused by a pulsed character of laser field for the ThomX typical laser pulse and the electron beam parameters. The emission angle $\theta = 1/\gamma$. Solid line corresponds to the envelope function in the form of Gaussian function $g(\xi) = \exp(-\xi^2)$, dotted line corresponds to Lorentz function $g(\xi) = (1+\xi^2)^{-1}$.

Thank you for attention!