Laser Compton scattering photon beams and other gamma-ray sources: Project for coherent gamma-ray source on basis of femtosecond laser at ILC MSU

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Новые гамма пучки
на основе фемтосекундных лазеров

Обратное комптоновское рассеяние

Томсоновское рассеяние

Фемтосекундный лазер с импульсной мощностью около 10 Дж обеспечивает следующие параметры γ -пучка :

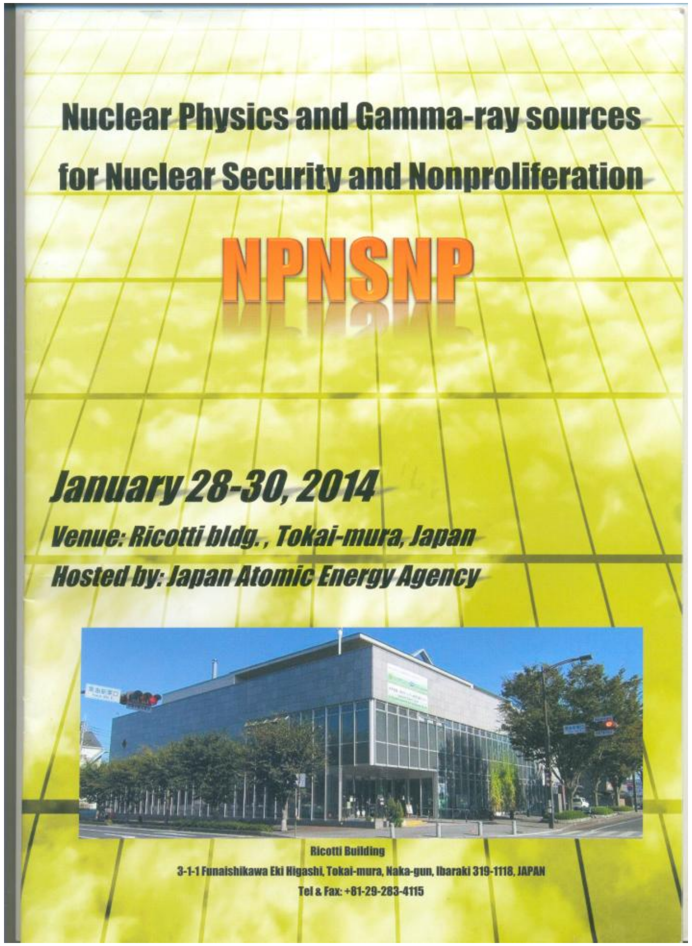
Энергия E_γ до 10 МэВ

Разброс $\Delta E_\gamma/E_\gamma$ до 10^{-5}

Интенсивность N_γ до 10^6 γ/s

Угол излучения до 1 мрад

Частота повторения до 100 Гц



Compton back scattering history

1963 – F.Arutunyan, V.Tumanyan. JETF 44 (1963) 6, 2100.
R.H.Milburn, Phys.Rev.Lett. 10 (1963) 3, 75

1964 – Moscow (Lebedev FIAN) – first experimental evidence

1976 - Frascati (LADONE - ADONE) – photonuclear physics

1984 - Novosibirsk Budker INP (ROKK – 1,2 – VEPP 3,4) meson photoproduction

1988 – Brookhaven BNL (LEGS - NSLS)

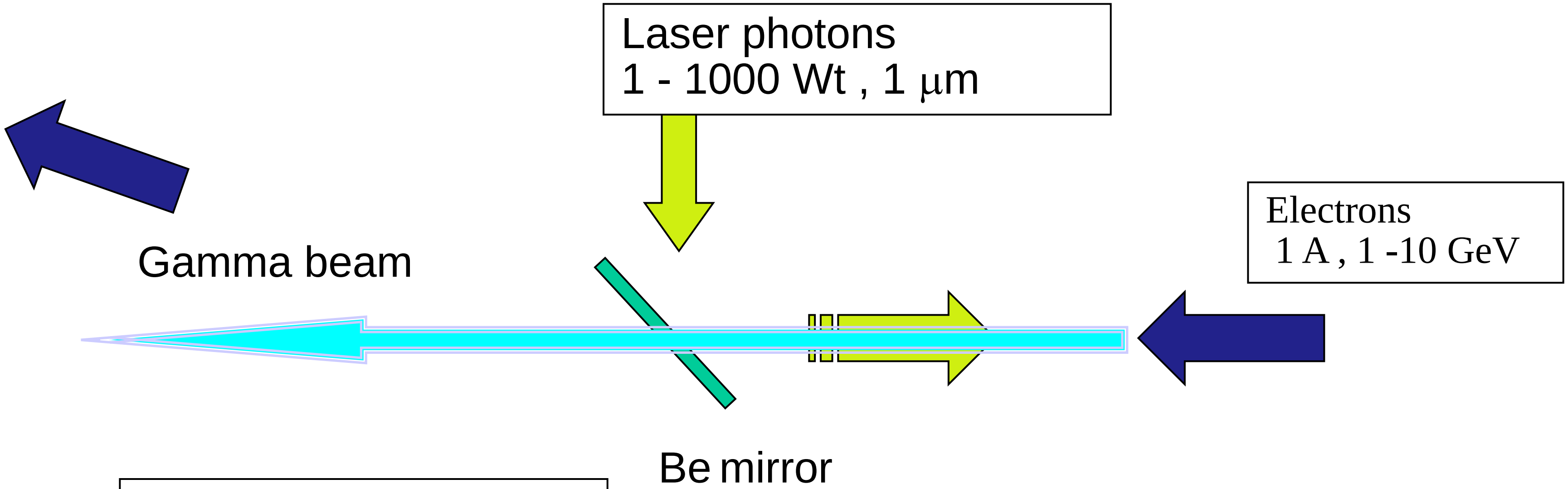
1995 – Grenoble (GRAAL – ESRF)

1998 – Osaka (LEPS - Spring-8)

2000 – Duke (HIgS -)

New history: FEMTOSECIND LASER DRIVEN GAMMA SOURCES

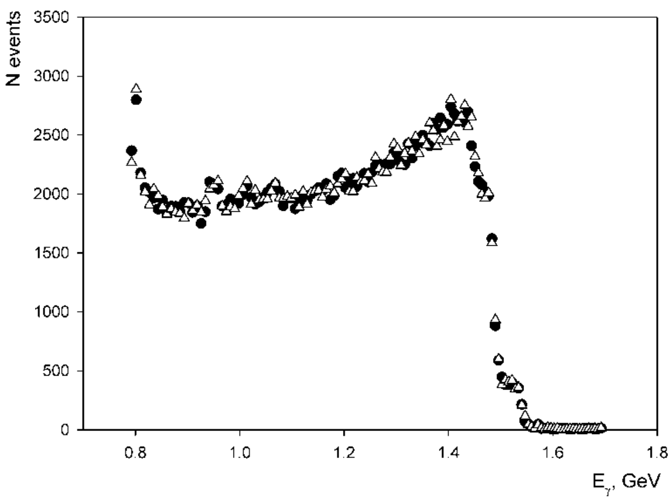
Compton back scattering technique



Argon (UV) $N_\gamma < 10^7\ \gamma/s$
CO_2 (IR) $< 10^{10}$
Recirculator $< 10^{15}$

$$E_\gamma = 4\gamma^2 \frac{\omega}{1 + n^2 + \lambda}$$

$n = \theta\gamma$, $\gamma = E_e/m_e$



Relativistic electromagnetic fields produced by femtosecond laser

Mourou G., Tajima T., Bulanov S.V. // Review of Modern Physics. 2006. V.78. P.309-371

Time duration — to 10^{-15} s (femtosecond)

Wave packet length — to 10 μm (10 wave lengths)

Pulse energy - to 100 J, power - to 10^{15} Wt (petawatt).

Focus on radius of 10 μm provides W = 10^{20} Wt/cm^2

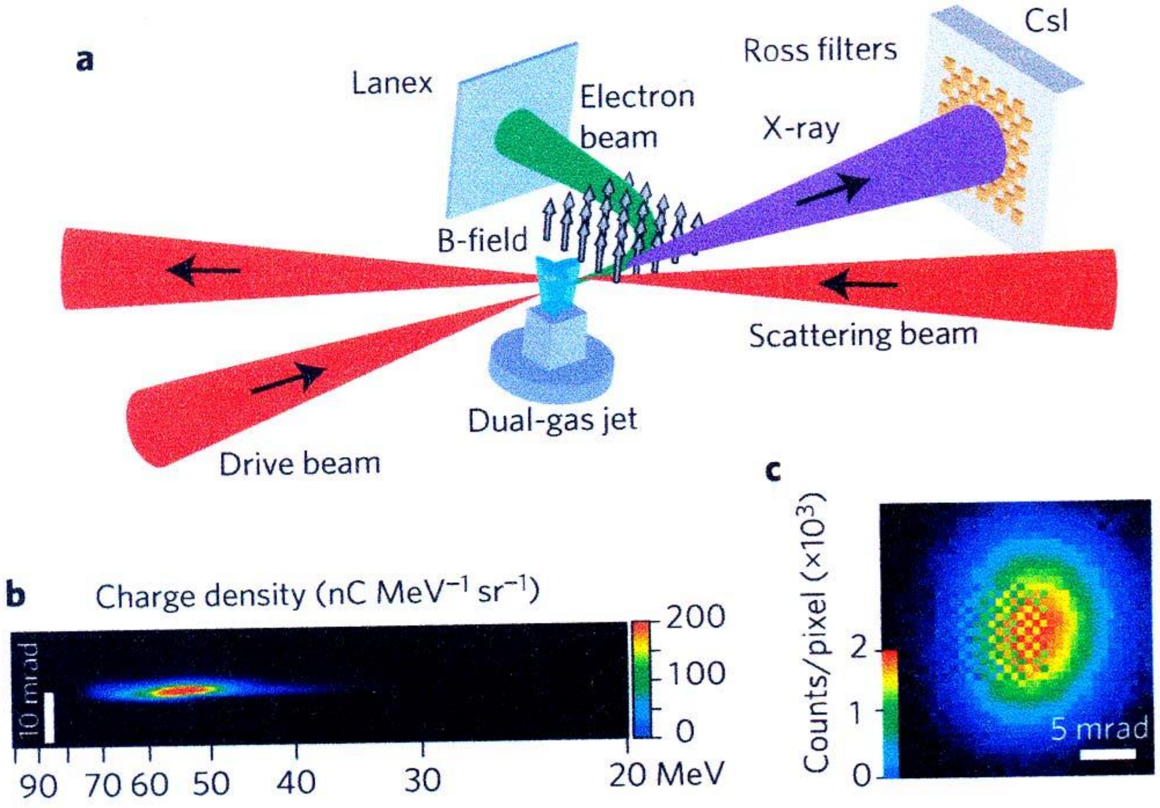
Electric field strength E = 10^{12} V/cm

(For comparison: in the hidrogen field E = 10^9 V/см., at mica breakdown - 10^6 V/см Uranium field E = 10^{11} V/cm, with relativistic compression – up to 10^{12} v/cm) .

At E ~10^{11} V/cm, respectively W ~10^{18} Вт/см^2 ($\lambda = 1$ μm) electron is accelerated to relativistic velosity being closed to the light one. Therefore such field is defined as the relativistic one .

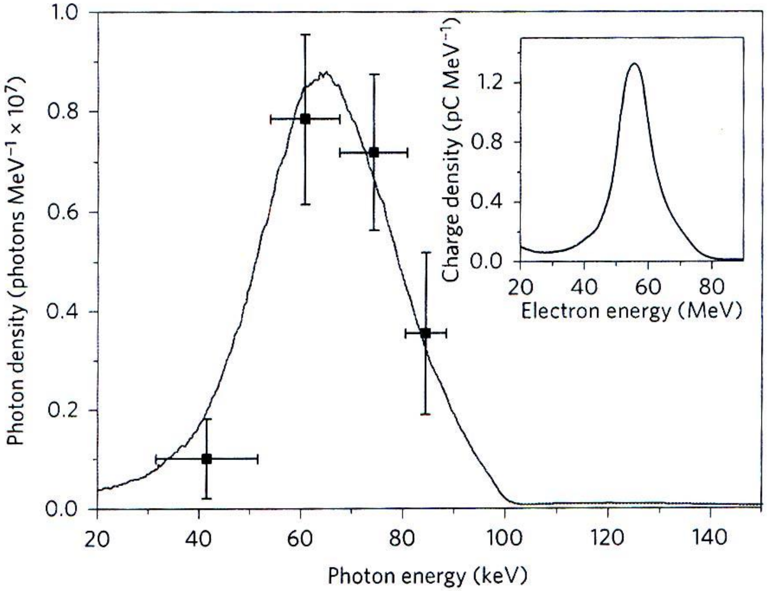
Nevertheless, direct photonuclear reactions (nuclear excitations) are forbidden.

Quasi-monoenergetic and tunable X-rays from a laser-driven Compton light source N. D. Powers, I. Ghebregziabher, G. Golovin, C. Liu, S. Chen, S. Banerjee, J. Zhang and D. P. Umstadter* Nature photonics letters (Nov. 2013) p.1-4.



3 × 10^{18} photons s^{-1} mm^{-2} $mrad^{-2}$ (per 0.1% bandwidth), 5–15 mrad.

Quasi-monoenergetic and tunable X-rays from a laser-driven Compton light source N. D. Powers, I. Ghebregziabher, G. Golovin, C. Liu, S. Chen, S. Banerjee, J. Zhang and D. P. Umstadter* Nature photonics letters (Nov. 2013) p.1-4.

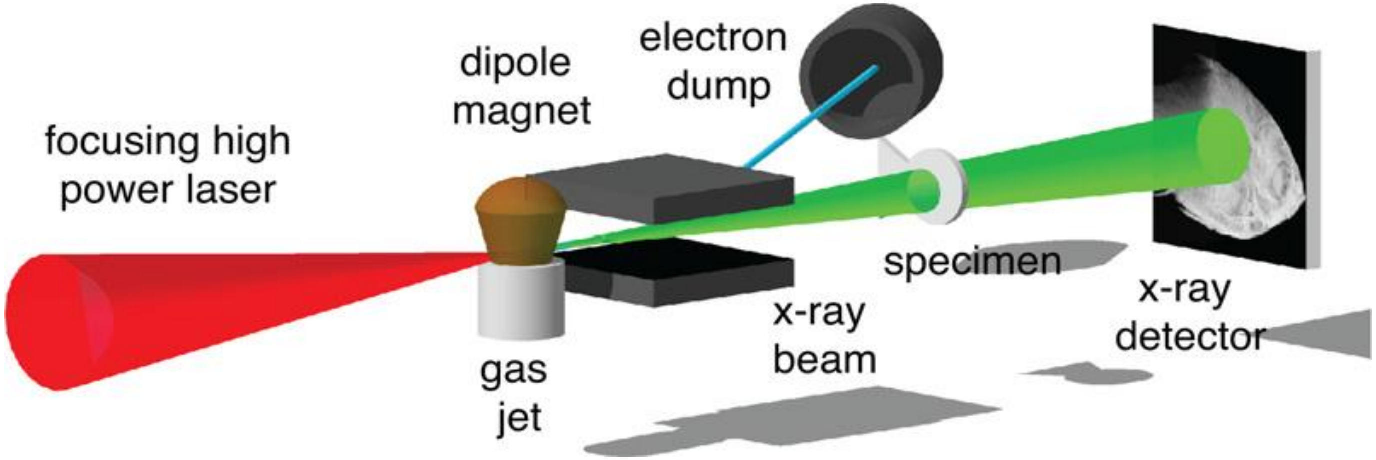


A broad synchrotron like spectrum with average photon energy (critical energy) of Ecrit ’ 10 keV like ESRF.

X-ray phase contrast imaging of biological specimens with femtosecond pulses of betatron radiation from a compact laser plasma wakefield (кильватер) accelerator

S. Kneip, C. McGuffey, F. Dollar, M. S. Bloom, V. Chvykov et al.

Appl. Phys. Lett. 99, 093701 (2011)

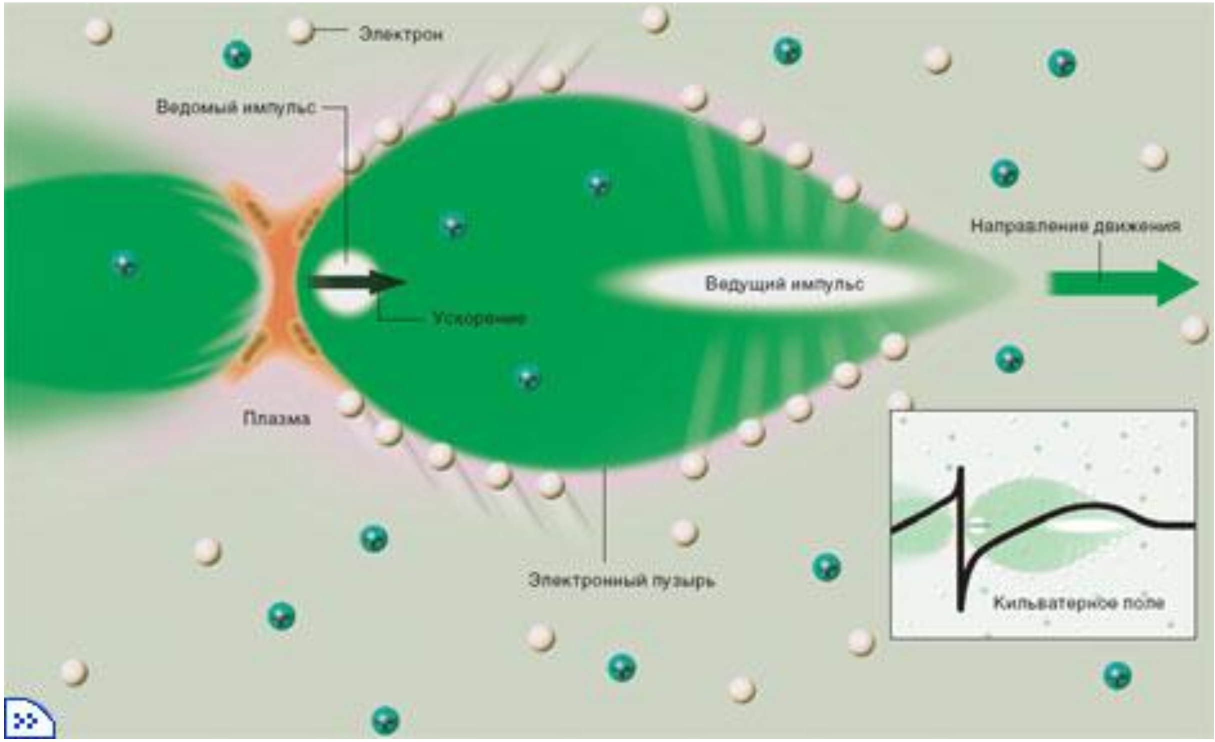


Hercules laser at the Center for Ultrafast Optical Science at the Uni.of Michigan, Ann Arbor.

W = 2*10^{19} W/cm^2 (Limit of 10^{20} ; MSU – 10 ^{19})
fully ionized plasma densities of 3*10^{18} cm^3.
Electron beams of 100 pC charge and peak energy of 120 MeV ($\Delta E/E$ = 3%) - 10^{12} е/имп
X-ray beam divergence is measured to be 5–15 mrad,
The x-rays intensity source size as determined with a penumbral imaging technique is found to be 1_3 lm,
= 10^6 photons/mrad^2 from x-ray calorimetry measurements with a ccd camera
The x-rays spectrum is consistent with a broad synchrotron like spectrum with average photon energy (critical energy) of E_{crit} = 10 keV.

Струя He с диаметром 3 мм и давлением , близким к атмосферному 3*10^19 /cm^3 ?

Ускоритель с кильватерным полем



Ускоряющая сила создается возмущенным распределением зарядов, которое называют кильватерным полем. Ведущий лазерный или электронный импульс выталкивает электроны плазмы (белые) на периферию, оставляя за собой область положительного заряда (зеленая). Она втягивает отрицательно заряженные электроны назад, и позади ведущего импульса формируется электронный пузырь. Вдоль оси распространения пучка электрическое поле (изображено внизу) напоминает очень крутую, готовую обрушиться океанскую волну. Кильватерное поле придает мощное ускорение ведомому электронному импульсу, захваченному задней частью пузыря.

≅

Напряженность ускоряющего кильватерного поля
Wake accelerating field strength

$$E_0 = cm\omega_p/e$$

Where c – light velocity, e and m- electron charge and mass, ω_p – plasma frequency

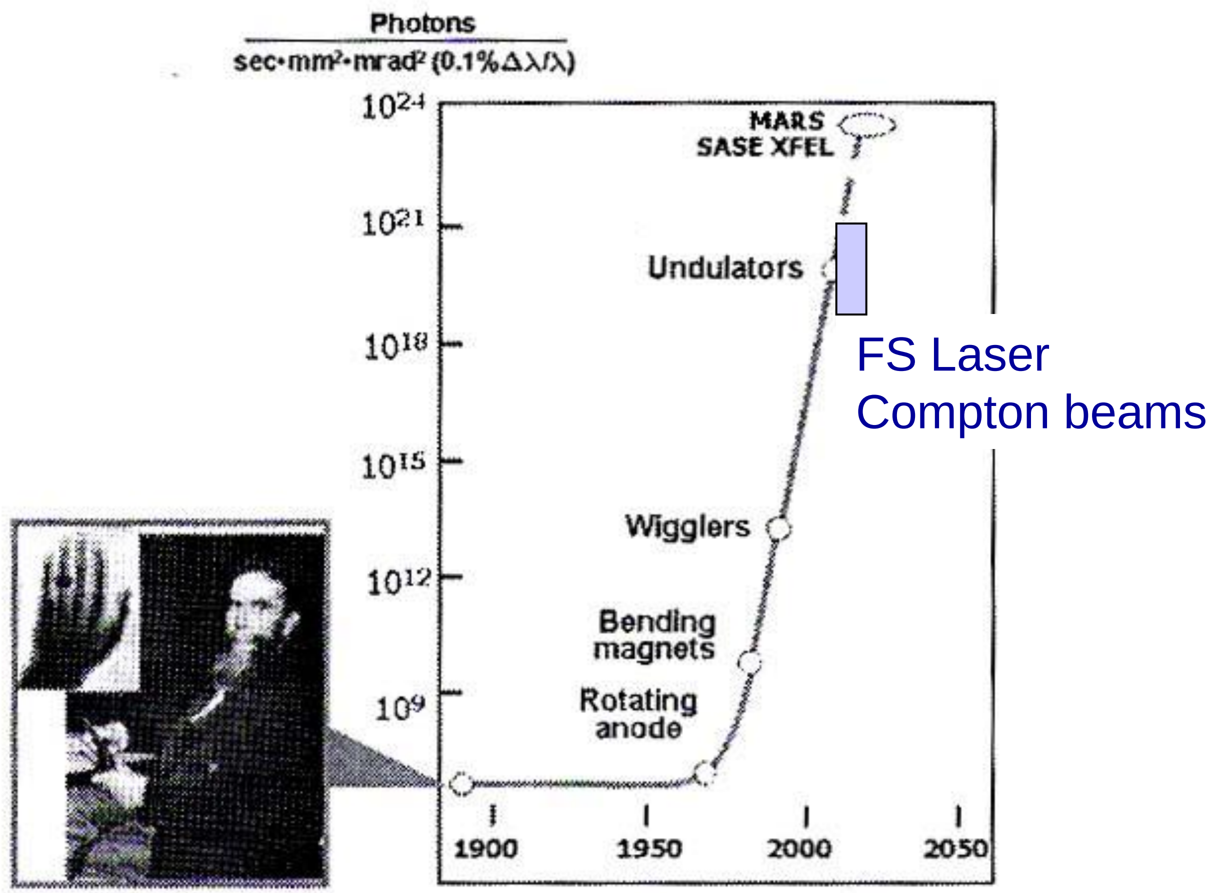
Using $\omega_p = (4\pi ne^2/m)^{1/2}$, где where n is a plasma density,

$$E_0[\text{В/м}] = 96\, n^{1/2}\, [\text{см}^{-3}]$$

At n = 10^{18} см $^{-3}$, $E_0 = 100$ **GeV/m**

Synchrotron radiation at storage rings

Brightness and total intensity



X-Ray imaging: Three color optics

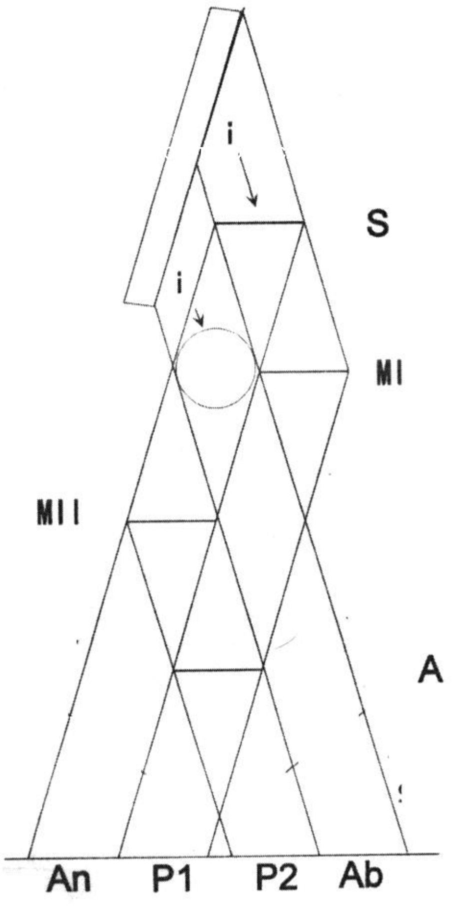
Medical Applications of Synchrotron Radiation / Eds M. Ando, C. Uyama. Tokyo, 1998

Simultaneously measured:

Absorption (Ab)

Refraction (An - "Dark field")

Phase contrast (P1,P2),



S – splitter

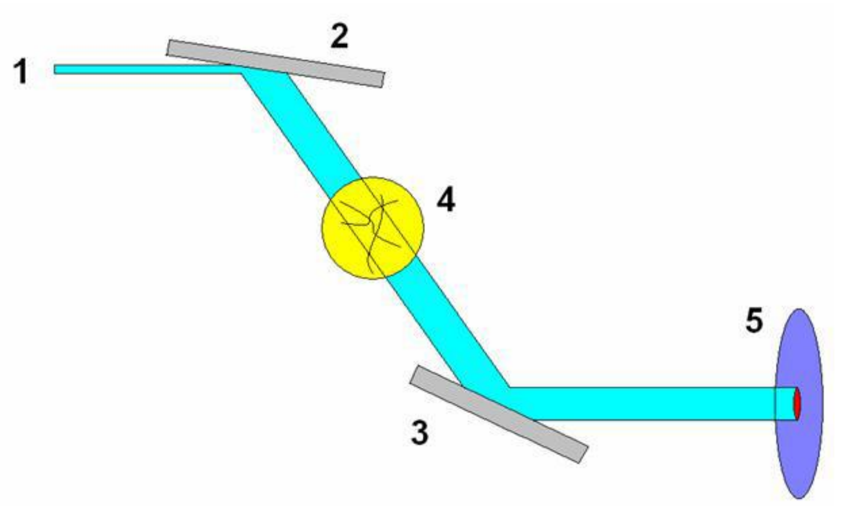
MI, MII – mirrors

Refraction contrast X-Ray diagnostics

Шильштейн С. Ш., Подурец К. М., Соменков В. А., Манушкин А. А. // Поверхность: рентгеновские, синхротронные и нейтронные исследования, 1996, №3, 231-241.

Новосибирск, ВЭПП-3,4 , Курчатовский источник СИ

Experimental scheme:



1- synchrotron radiation beam,

2- crystal monochromator,

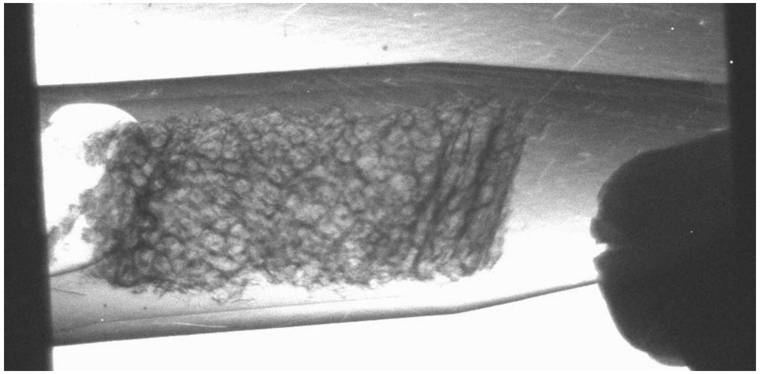
3- crystal analyzer,

4- object,

5- detector.

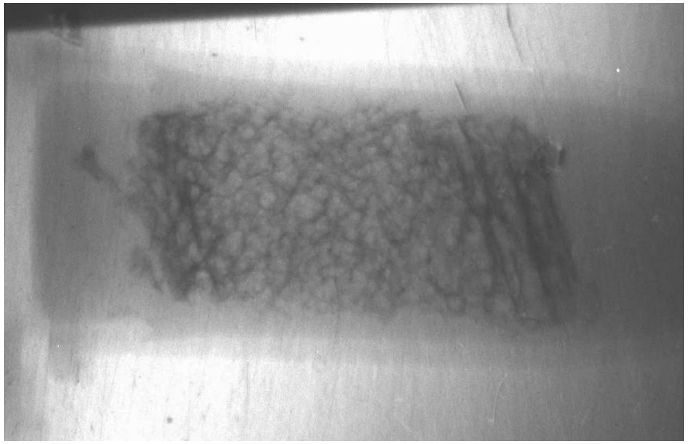
K.M.Podurets, D.K.Pogorelyi, A.A.Manushkin, V.G.Nedorezov, V.A.Somenkov, S.A.Shchetinkin, N.K.Kononov and A.P.Kuvardina, Experiments on Refraction Imaging of Biological Objects at the Kurchatov Synchrotron Radiation Source, Crystallography Reports Vol. 49, Suppl. 1, 2004 p.50-54) .

Угловое отклонение пучка на границе воздух—объект в приближении геометрической оптики :



$$\delta\alpha = (1 - n)\cdot \mathrm{ctg}\,\alpha$$

Изменение коэффициента преломления на границе органической ткани с воздухом:



$$(1 - n) = 1.5\cdot 10^{-6}\lambda^2$$

M.Ando e.a. Crystal analyser-based X-ray phase contrast imaging in the dark field: implementation and evaluation using excised tissue specimens

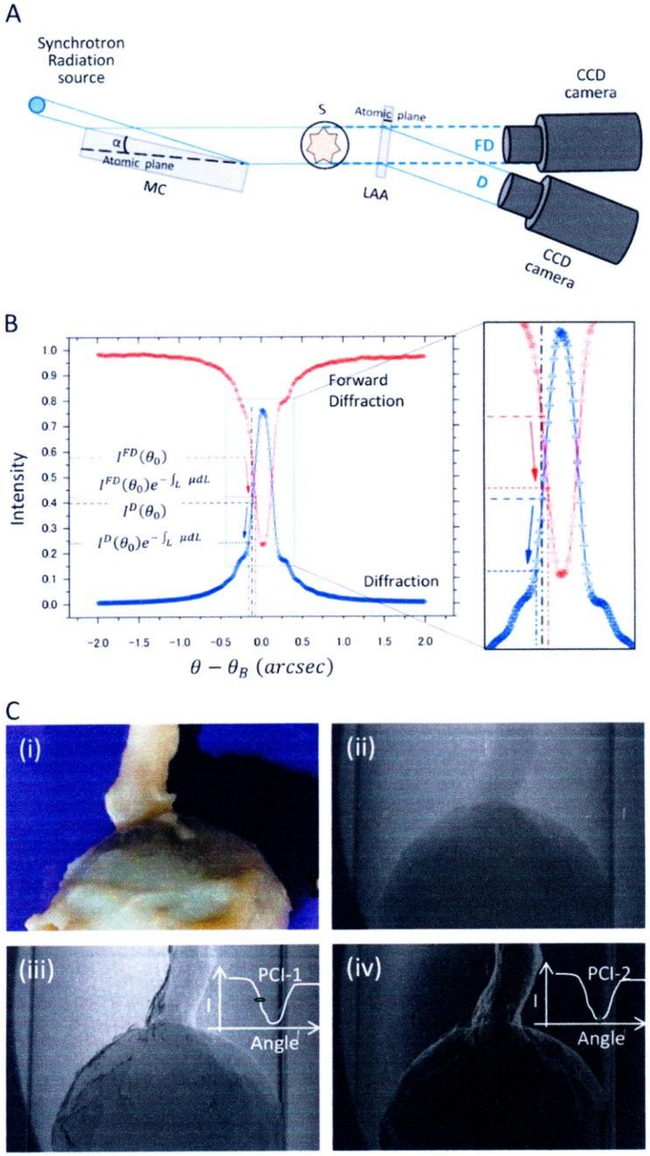
European Radiology (2013) ISSN 0938-7994

Objectives: the soft tissue discrimination capability of X-ray dark-field imaging (XDFI) using a variety of human tissue specimens.

Methods: The experimental setup for XDFI comprises an X-ray source, an asymmetrically cut Bragg-type monochromator-collimator (MC), a Laue-case angle analyser (LAA) and a CCD camera. The specimen is placed between the MC and the LAA. For the light source, we used the beamline BL14C on a 2.5-GeV storage ring in the KEK Photon Factory, Tsukuba,Japan.

Results: In the eye specimen, phase contrast images from XDFI were able to discriminate soft-tissue structures, such as the iris, separated by aqueous humour on both sides, which have nearly equal absorption. Superiority of XDFI in imaging soft tissue was further demonstrated with a diseased iliac artery containing atherosclerotic plaque and breast samples with benign and malignant tumours. XDFI on breast tumours discriminated between the normal and diseased terminal dictlobular unit and between invasive and in-situ cancer.

Conclusions: X-ray phase, as detected by XDFI, has superior contrast over absorption for soft tissue processes such as atherosclerotic plaque and breast cance



3×10^{18} photons s^{-1} mm^{-2} $mrad^{-2}$ (per 0.1% bandwidth), 5–15 mrad.

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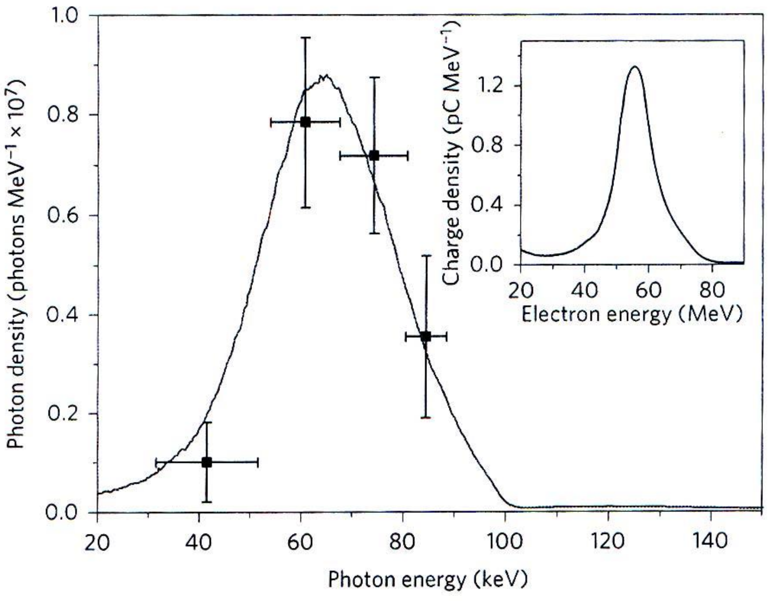

A broad synchrotron like spectrum with average photon energy (critical energy) of Ecrit ’ 10 keV like ESRF.

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Appl. Phys. Lett. 99, 093701 (2011)

X-ray absorption contrast image of

a - an orange tetra fish

b- a damselfly

[u=2,79 m]

$$L_{\text{trans}} = \frac{\lambda u}{2\pi w_{x,y}},$$

x-ray phase ontrast image of

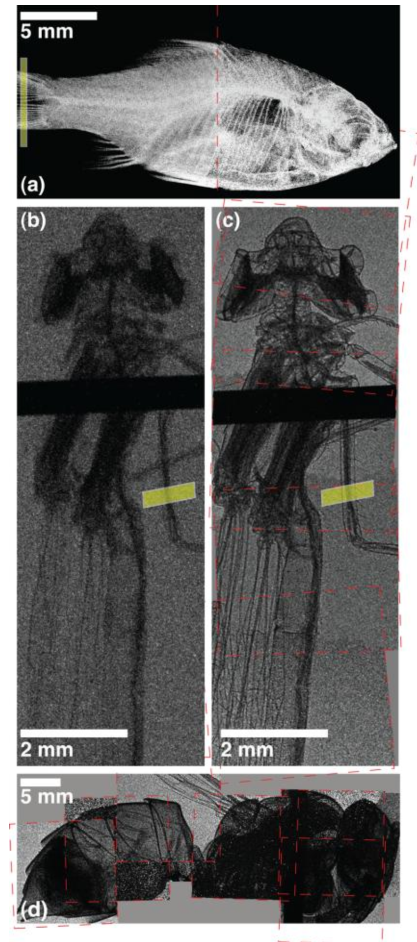
c- a damselfly

d - a yellow jacket.

[u = 0,44 m] L_{trans} - 10 μm

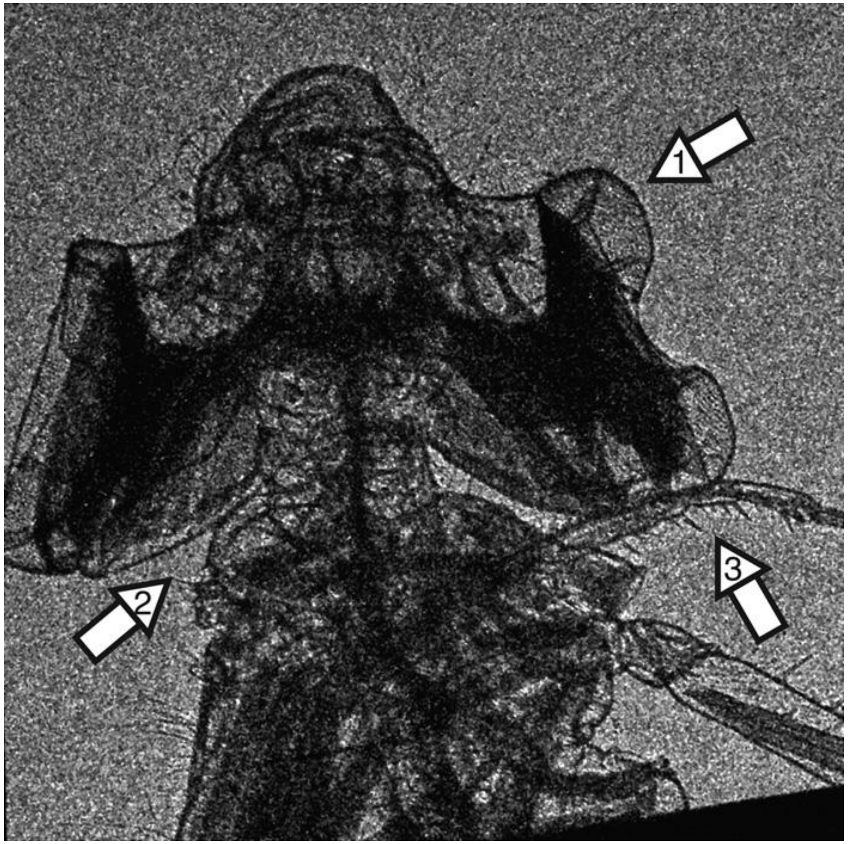
Images are taken with betatron radiation from a laser wakefield accelerator. The spectrum is synchrotron like with E_{crit} ’ 10 keV.

The phase contrast images are taken in a single shot 30 fs exposure.

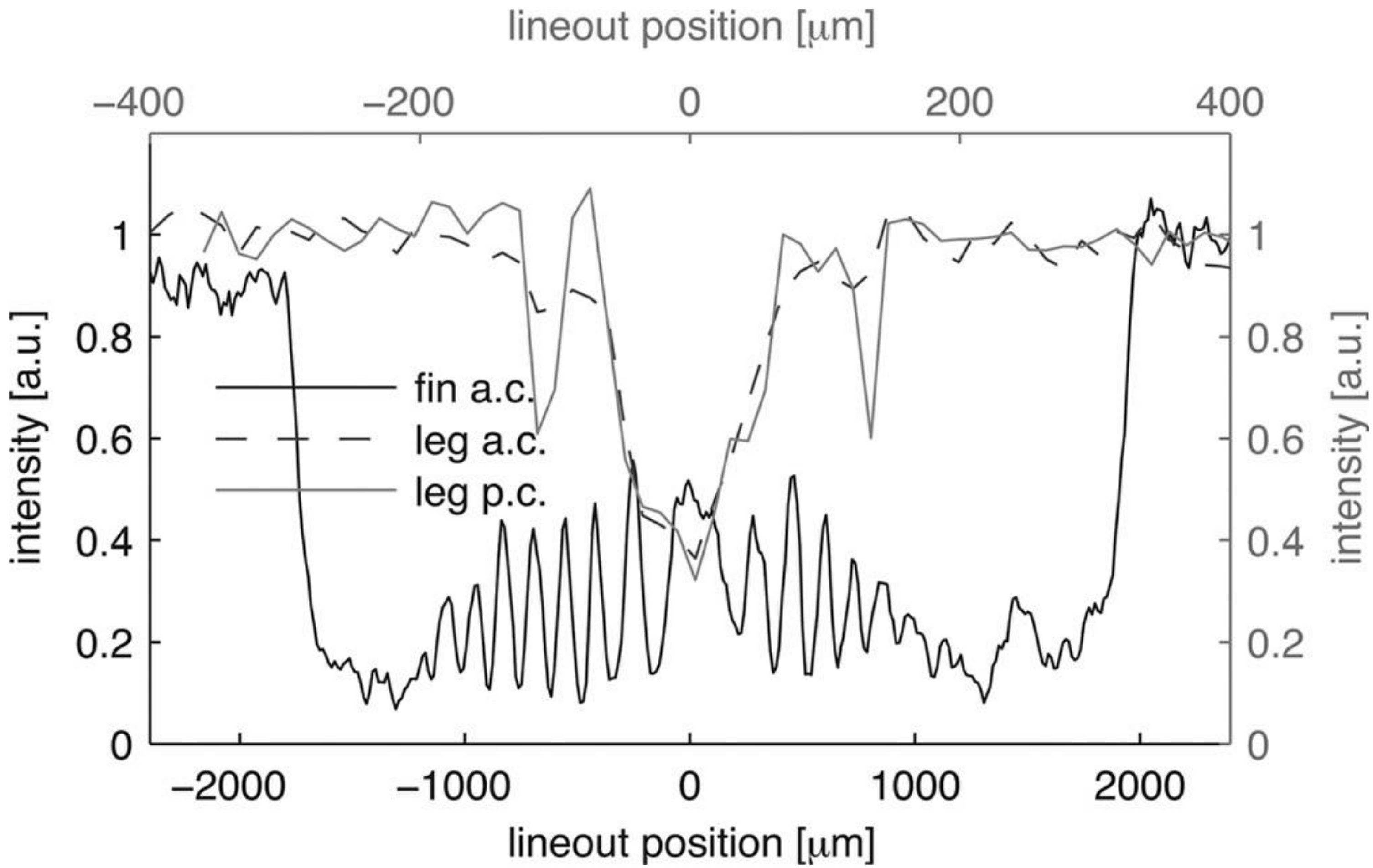


Single shot 30 fs exposure x-ray phase contrast image of the head of a damselfly. Notice details of the compound eye (1), exoskeleton (2), and leg with hairs (3).

- Each laser pulse delivers
- 30 fs burst of x-rays 10 keV,
- with a peak brightness of 10^{22} ph/s/mm^2/mrad^2 /0.1% bandwidth,
- comparable to conventional 3rd generation synchrotrons, making possible high contrast imaging in a single shot.

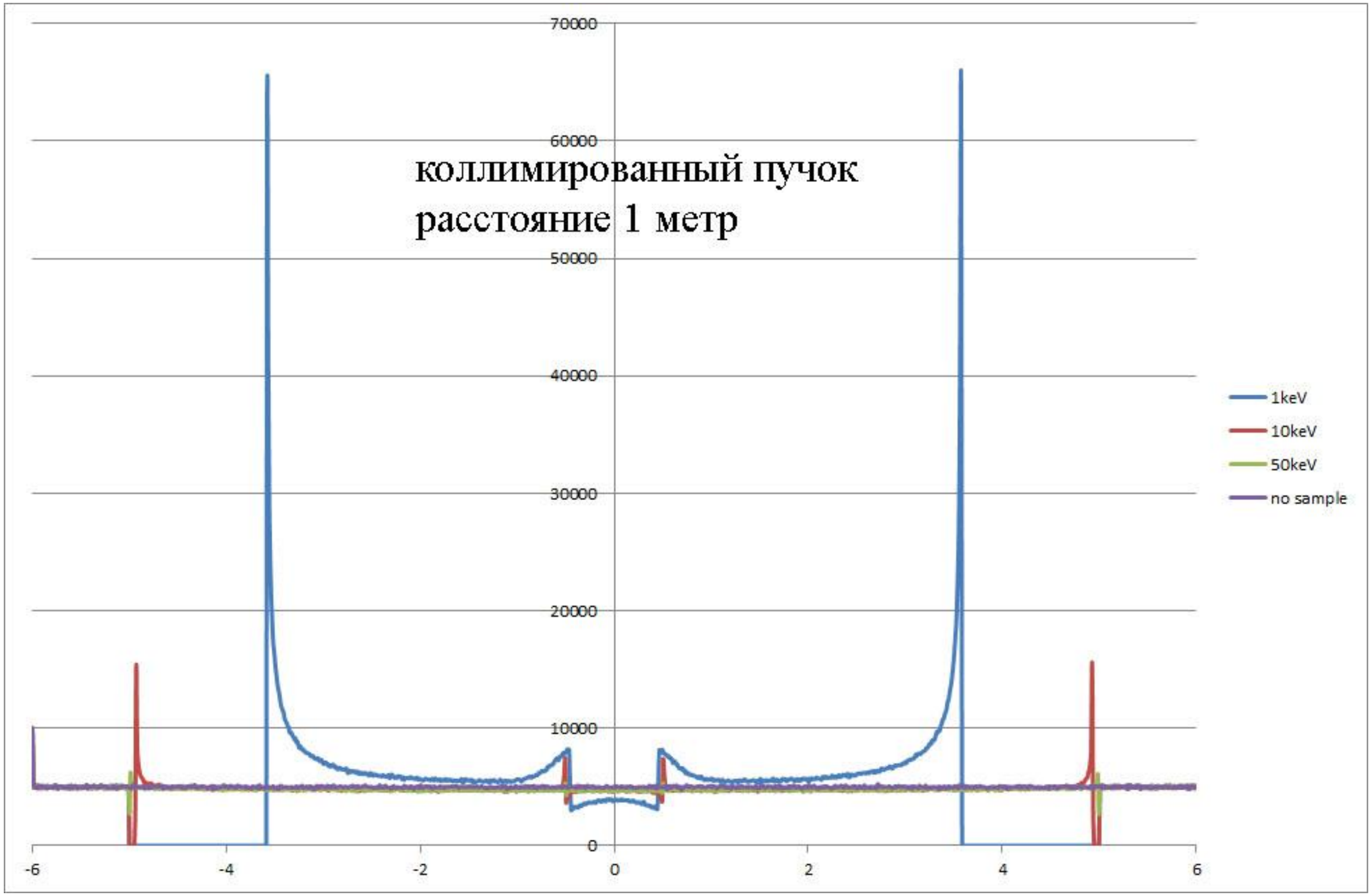


contrast


lineout position [μm]
−400
−200
0
200
400
1
0.8
0.6
0.4
0.2
0
intensity [a.u.]
fin a.c.
leg a.c.
leg p.c.
−2000
−1000
0
1000
2000
lineout position [μm]
intensity [a.u.]

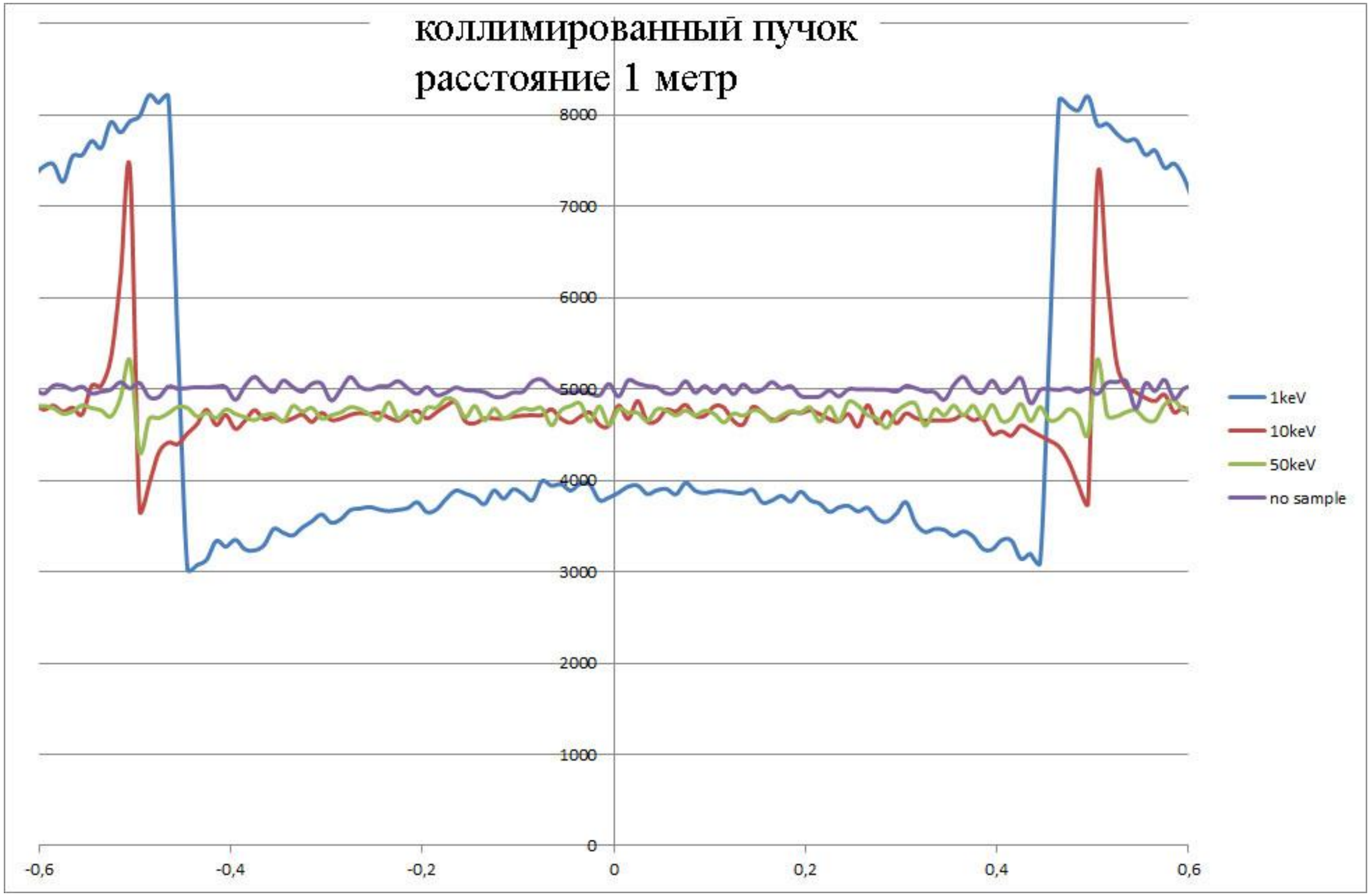
Моделирование
кварцевая леска (1 мм) в воде (1 см)

А.Туринге, частное сообщение



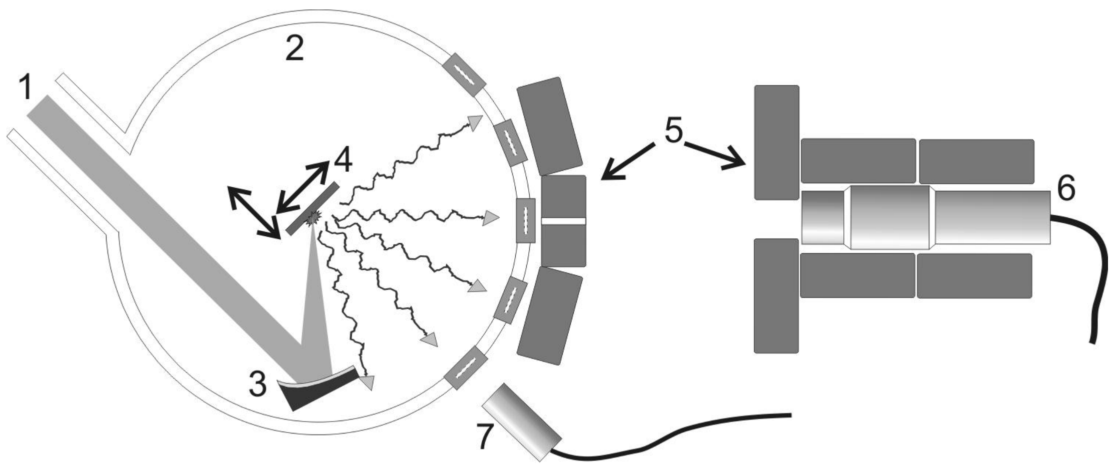
Моделирование
кварцевая леска (1 мм) в воде (1 см)

А.Туринге, частное сообщение



Experimental setup at ILC MSU : Lomonosov MSU[1] , INR RAS[2], Lebedev FIAN [3]

Ivanov K.A., Shulyapov S.A., Turinge A.A., Brantov A.V., Uryupina D.S., Volkov R.V., Rusakov A.V., Djilkibaev R.M., Nedorezov V.G.,Bychenkov V.Yu, Savel'ev A.B.
Contributions to Plasma Physics, 53, 2 (2013) 116-12



1 – laser radiation, 2 – vacuum chamber, 3 – off-axis parabola, 4 –target on a motorized 3D translation stage, 5 – lead blocks and collimator, 6 – X-ray detector in single quantum regime, 7 – X-ray yield monitor

Laser parameters: 50 fs, 10mJ, 800 nm, 10Hz, peak intensity $2{\cdot}10^{18}$ W/cm^2
contrast on the nanosecond time scale - 2.10^{-6}

Laser facility at ILC MSU

Reaction chamber

Wave length 800 nm,

Impulse length 50 fc,

Frequency 10 Hz,

Pulse energy 50 mJ,

Focusing diameter 4 μm.

Beam intensity on the target 10^{19} W/cm^2,

being equivalent to the electron

quasi-temperature of ~1 MэВ.

Задача имеет междисциплинарный характер:

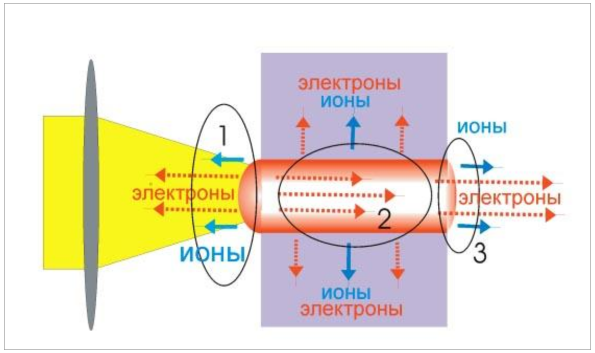
1) Физика плазмы : механизмы ускорения электронов Эксперимент и моделирование

A.V.Andreev, V.M.Gordienko, A.B.Savel'ev. "Nuclear processes in the high temperature plasma induced by the super short laser pulse" Quantum electronics 31,11 (2001) 941-956.

"At energy concentration of 10^{11} J/cm^3 the energy transfer to separated **atom** can exceed 10 MeV while the binding energy for **nucleon** is near 8 MeV".

High temperature electron production mechanisms (atomic processes)

at relatively low intensity $I_m < 10^{17}$ W/cm^2 :



- Resonance absorption, $\lambda/L > 1$
- Vacuum heat, $\lambda L < 1$
- Anomalous skin-effect $\lambda L << 1$

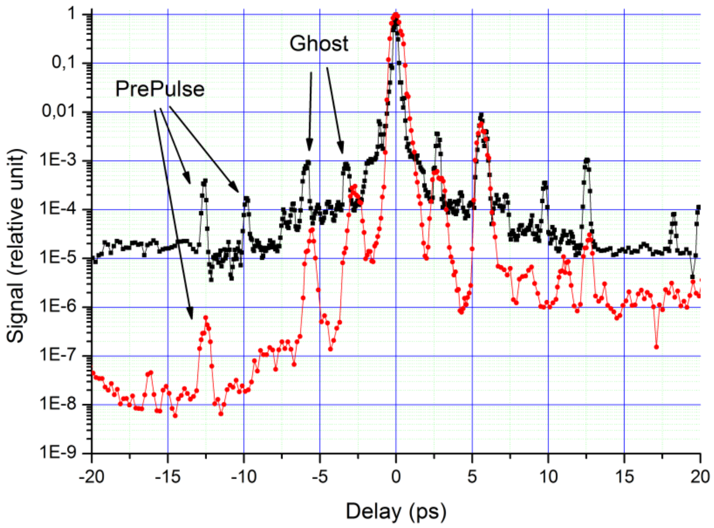
$L = (d\ln N_e/dz)^{-1}$

Runs /03/2013

•FIXED parameters
Laser Ti-Saphire 805 нм , 10 Hz
Target Fe
Contrast - 10^{-8} *
Polarization
Pre-pulse 12.5 ps, 12,5 ns (см.figure)

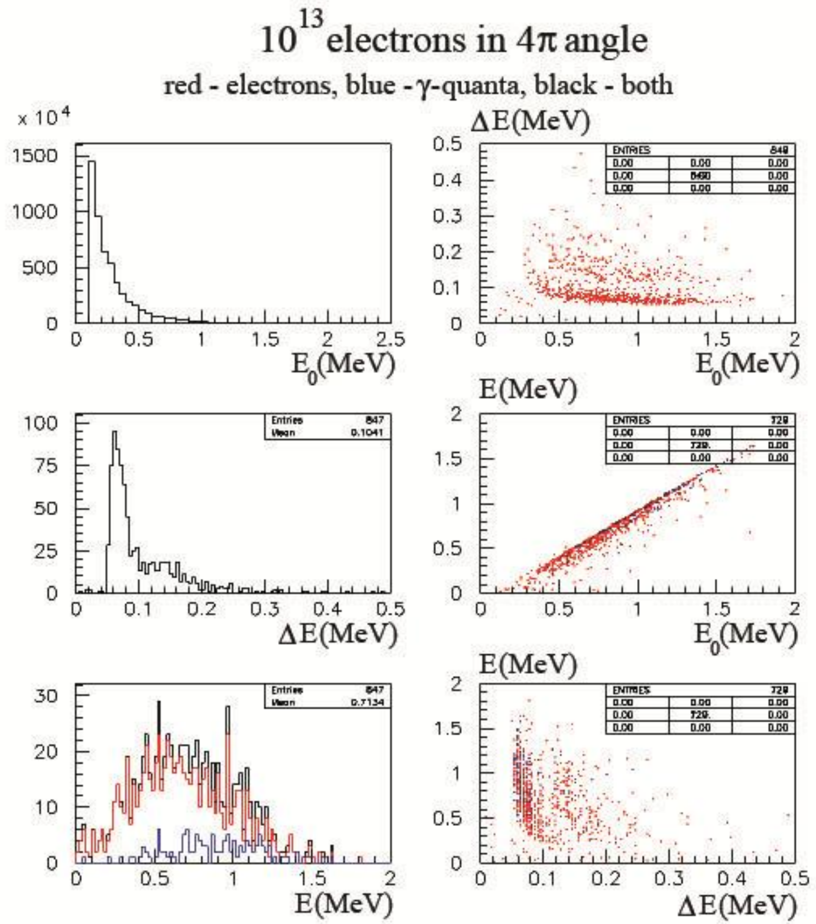
•VARIABLE parameters :
Energy $5*10^{17}$ - $2*10^{18}$
Duration 45 – 170 fs
Filters Cu 0.5 – 3.6 мм Cu2 мм , Pb 6 mm,
Shield Pb 50 mm

Correlation function
(2012 – black, 2013 – red).



Simulation of bremsstrahlung from interaction of a femtosecond terawatt laser pulses with matter . A.Turinge , A. Rusakov, A. Savel'ev, A. Brantov, V. Bychenkov. Proc.EMIN-2012,167- 171

MANDOR + GEANT

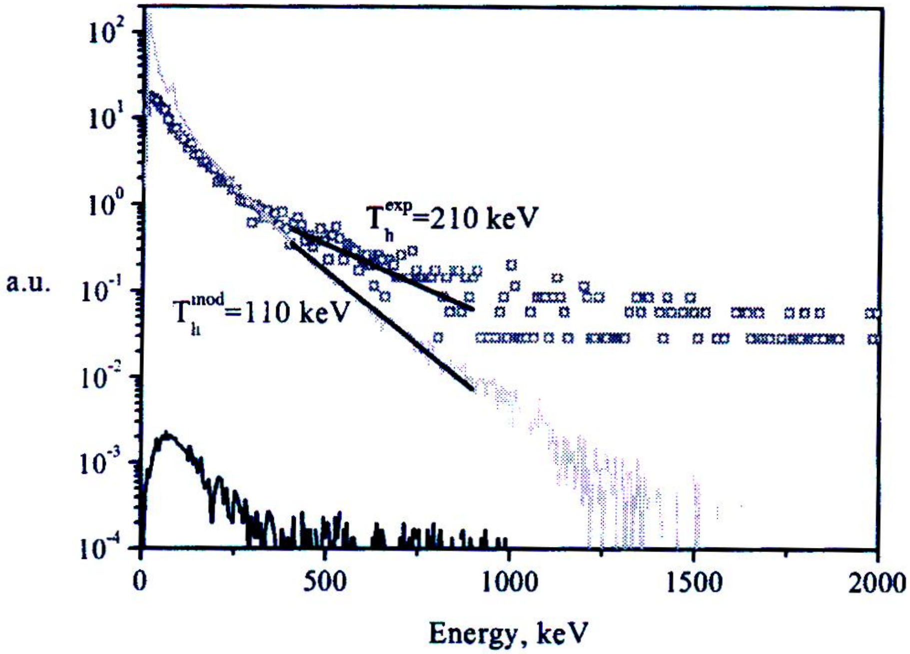


Experiment and simulations
Single photon regime

Squares – photon energy spectrum (experimental results) ;

Below: Backgrounds from
lead blocks, chamber walls etc.)

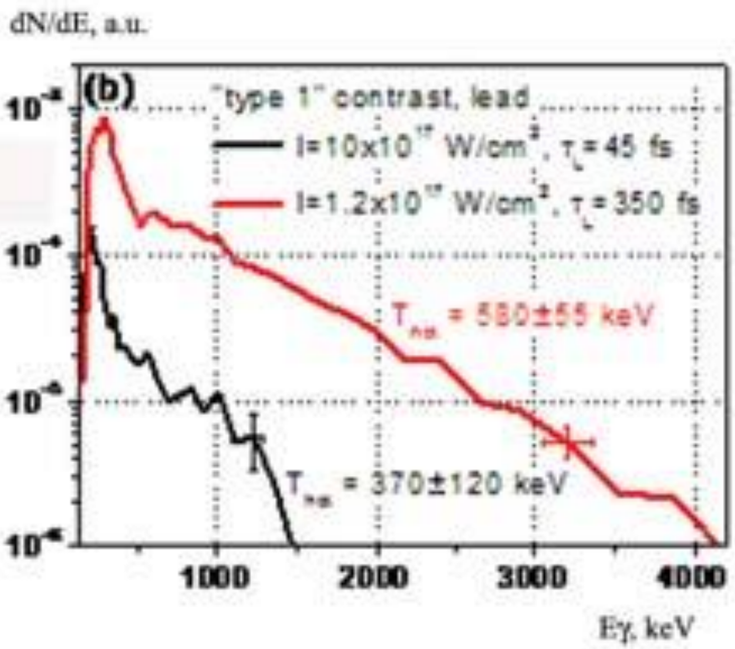
Straight lines – approximation (slope of two exponents)

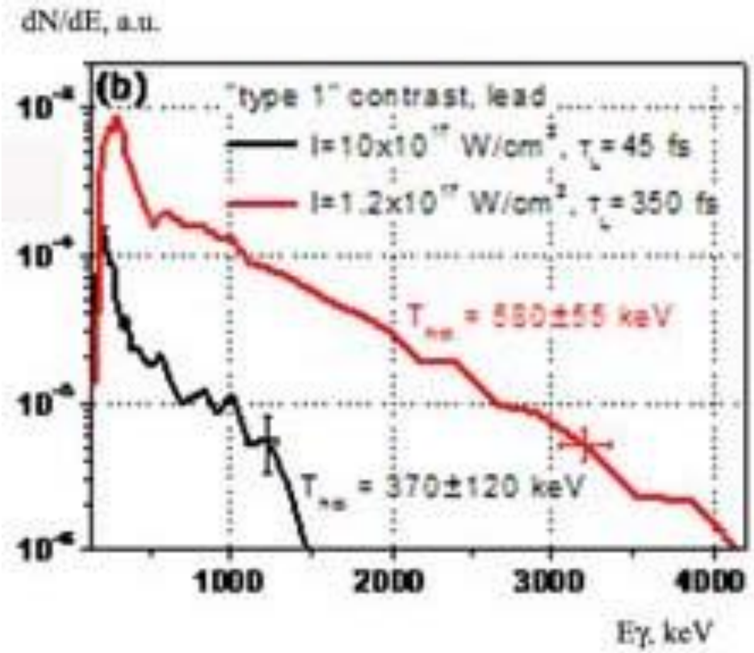


Фотоядерные методы + ускорители :

Измерение потоков и спектров электронов и фотонов с энергией до 100 МэВ.
Мониторирование параметров лазера в отдельных импульсах излучения,

Спектры фотонов из металлической мишени – последние данные :

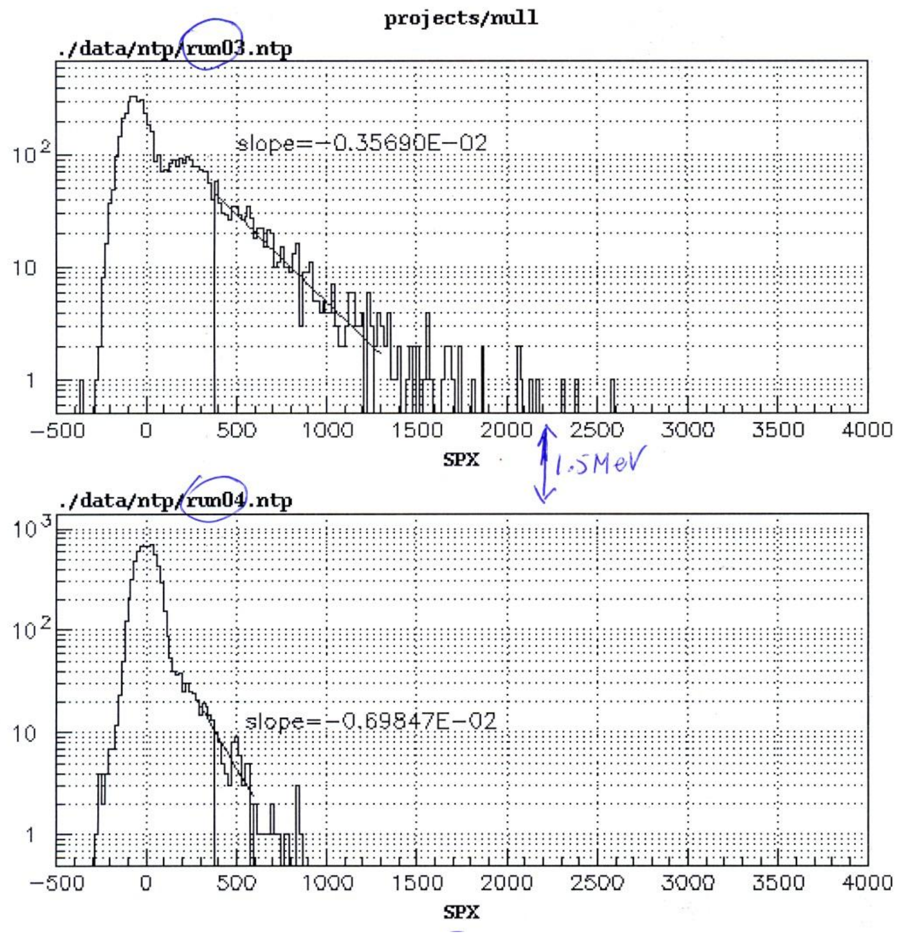




Photon spectra at different conditions

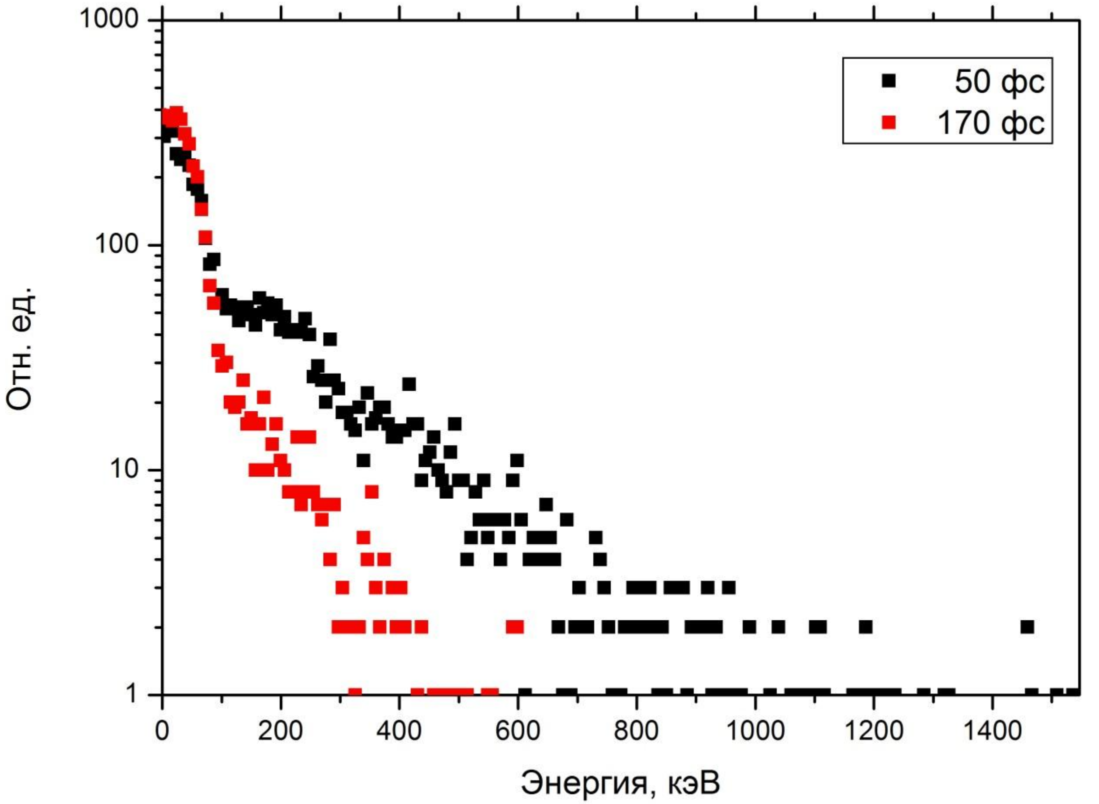
21.03.2013

run 3 : Target – Fe, E = 19.5 mJ, t = 45 fs.
run 4 : Target – Cu



Dependence of photon spectrum on the laser pulse length
filter Cu 3.6 мм Single photon regime

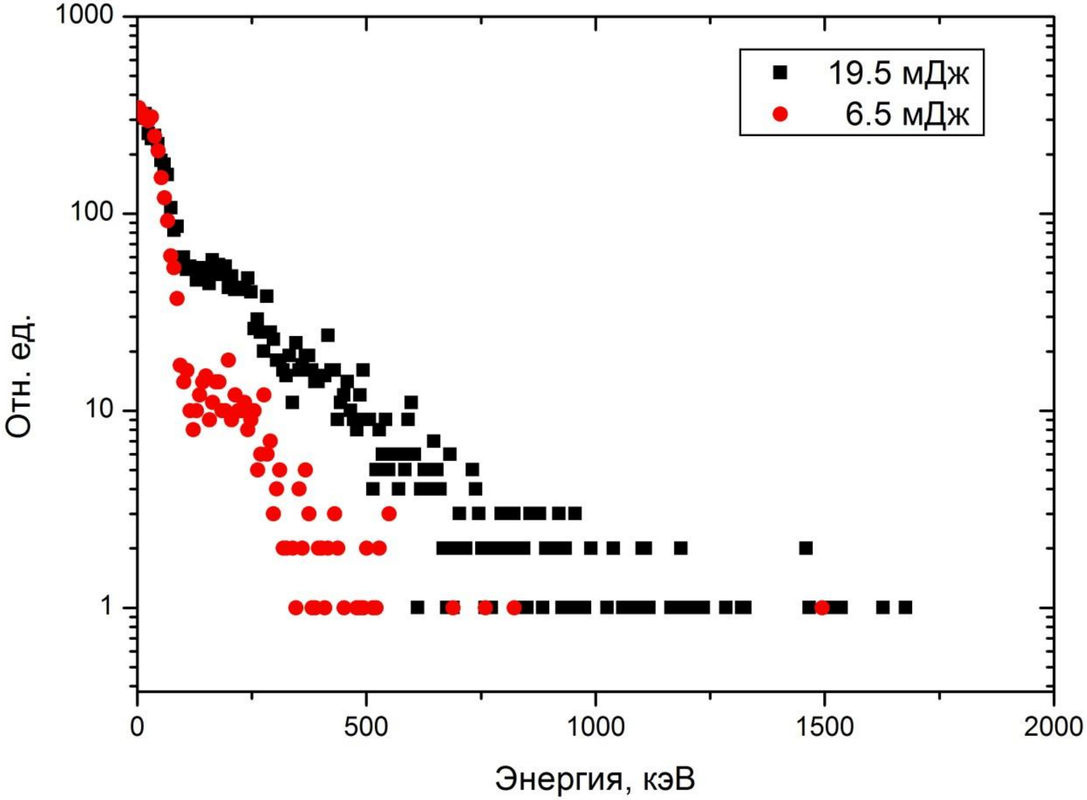
A.V.Rusakov
Study of electromagnetic radiation from the iron target, irradiated by femtosecond laser pulses , NUCLEUS -2013, Friday, Section V, Mephi, Moscow



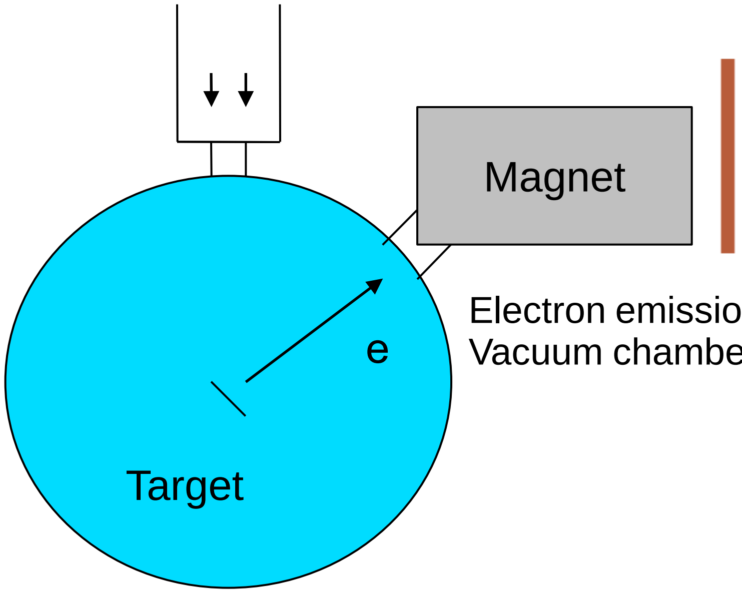
Dependence of photon spectrum on pulse energy , filter Cu 3.6 mm

A.V.Rusakov

Study of electromagnetic radiation from the iron target, irradiated by femtosecond laser pulses , Friday, Section V



Electron magnetic spectrometer



Coordinate detector in the focal plane
1 mm resolution

Electron emission angle fixed
Vacuum chamber diameter 40 cm

Radiation point 10 x 10 μc diameter
Electron energy of 10 keV till 50 MeV.
Electron pulse flux to 10^6 ./s , frequency 10 Hz

Energy ranges for 1% resolution : 100 — 1000 keV, 1 — 10 MeV, 10 — 50 MeV.

Other gamma ray sources :

Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons

A. Chilingarian e.a. PHYSICAL REVIEW D 82, 043009 (2010)

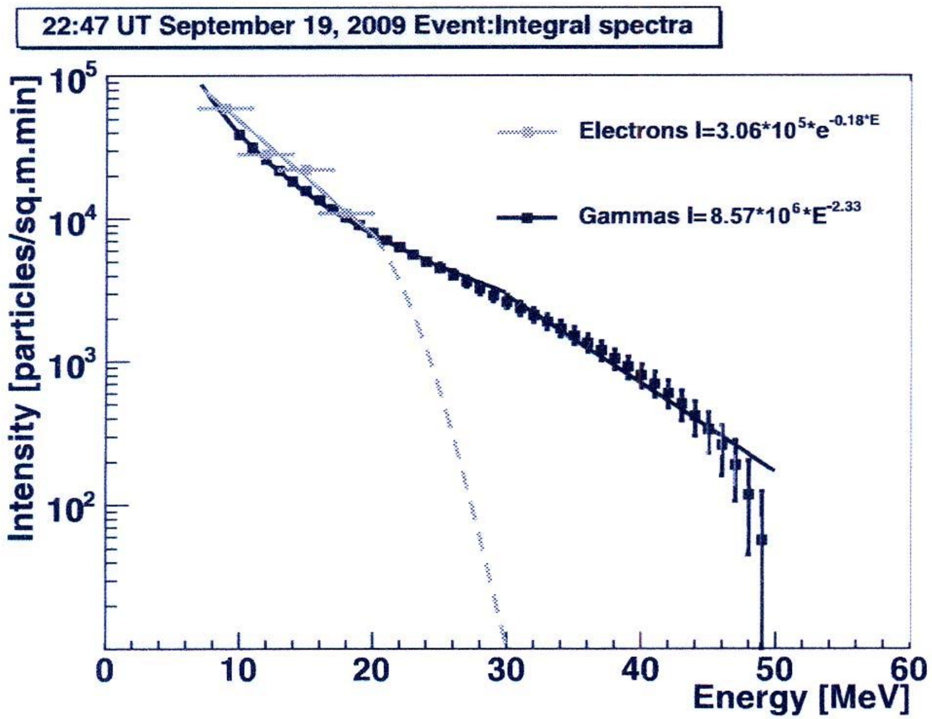


FIG. 7. Unfolded electron and gamma ray spectra fitted by exponential and power functions.

Заключение

Имеющиеся на сегодня результаты по фазовому контрасту на фемтосекундных лазерах носят демонстрационный, не систематический характер.

Нужны систематические исследования и выбор оптимальных параметров лазерно – плазменной установки – мощность , временная структура (пред-импульс), поляризация, фокусировка, контраст, мишень, и др.

Эксперимент + моделирование

Лазер – плазма – ускоритель - фотоядерные методы