



Методики синхротронного излучения для исследования динамических процессов

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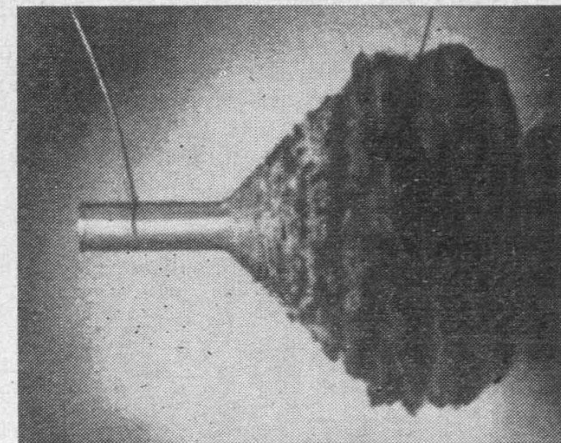
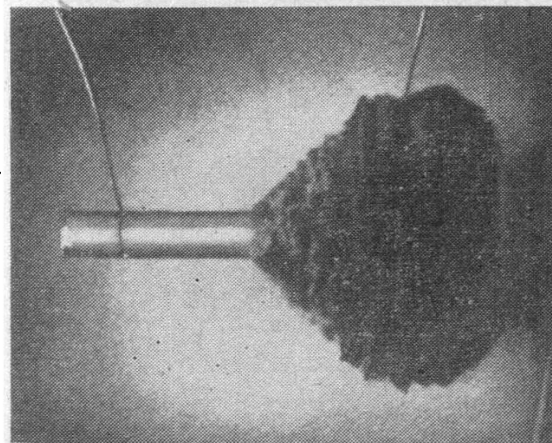
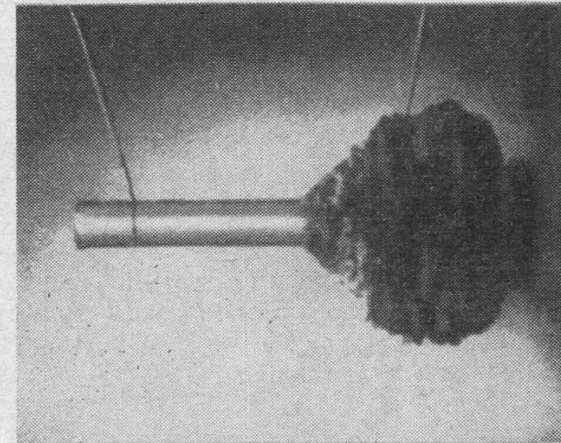
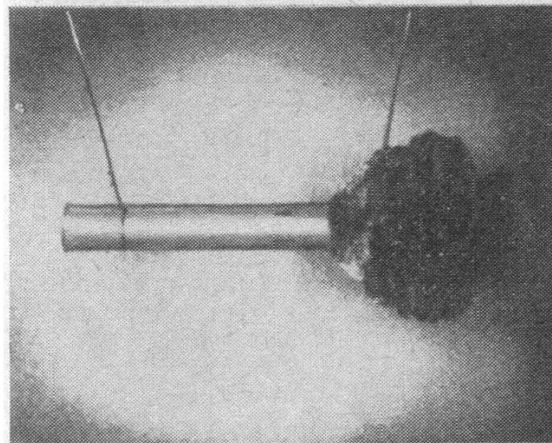
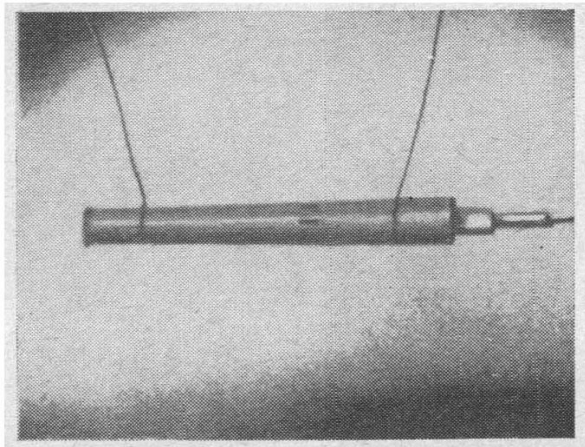
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<http://ancient.hydro.nsc.ru/srexpl>

- Parameters of experimental station on VEPP3/VEPP4.
- High velocity x-ray radiography of detonation and shock waves.
- Tomography of mechanical parameters of detonation wave.
- Carbon condensation at detonation wave.
- Detonation synthesis of metal particle for catalysis.
- Investigation of nanothermites.

Основные параметры детонационного течения



$$D = 8 \text{ км/с}$$

$$P = 10\text{-}30 \text{ ГПа}$$

$$T = 3\text{-}5 \cdot 10^3 \text{ К}$$

$$t = 10^{-6} \text{ с}$$

$$l = 1 \text{ мм}$$

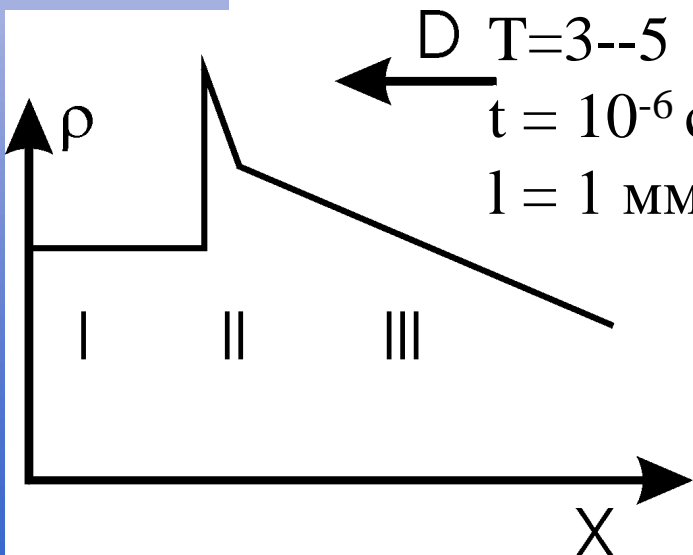
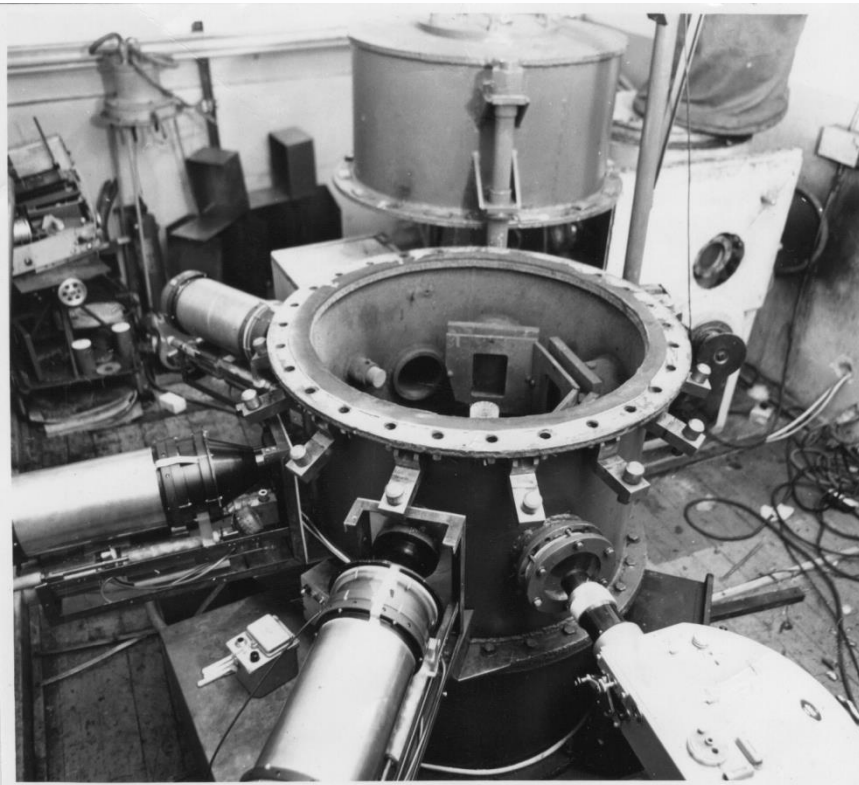
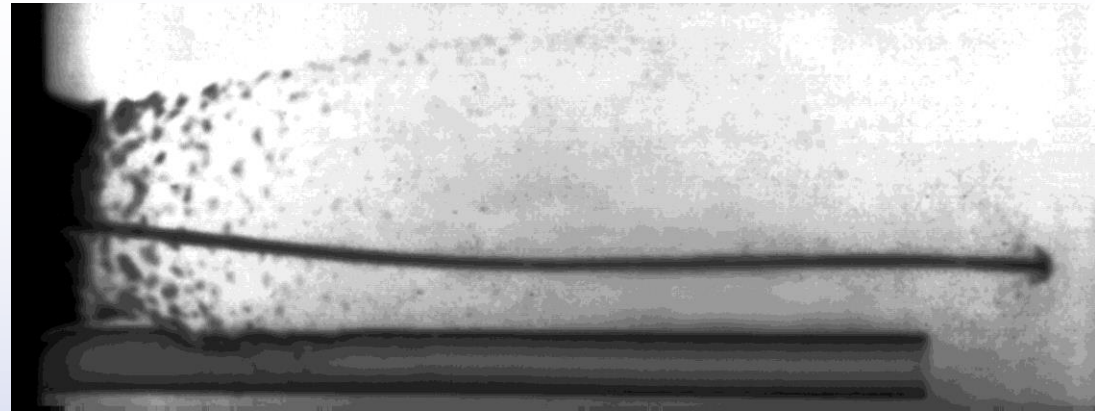


Рис. 32а. Фотографии детонирующего заряда динамита (большая скорость детонации 5400 м/с). Интервал между кадрами 5 мкс, время экспозиции 0,1 мкс.

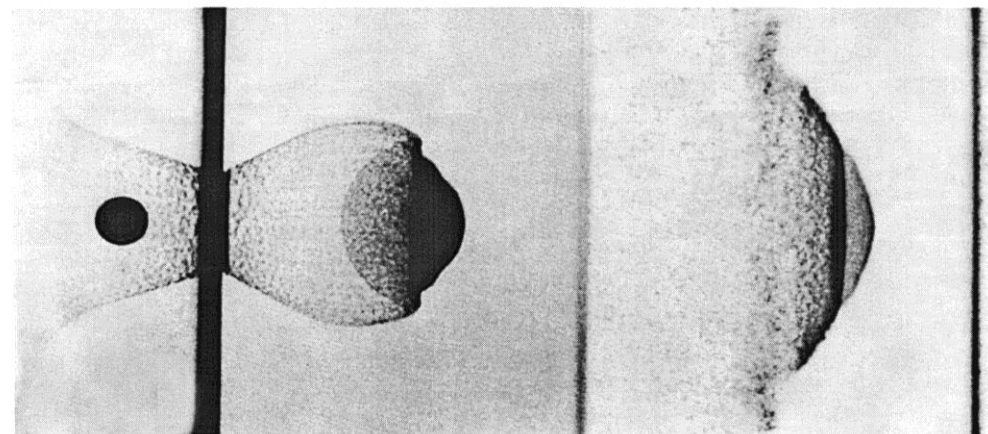
Скоростная рентгенография



Взрывная камера для съёмки кумулятивных струй с тремя ПИР-600 и СФР в подвале главного корпуса Института гидродинамики.



Металлическая струя от кумулятивного заряда после преодоления стальной стенки. Скорость головы струи – 6 километров в секунду. Видна пелена из осколков, внедрение фрагментов пелены в стенку трубы (внизу).



Рентгенограмма запреградного облака осколков, образующегося при ударе 9-мм шарика из алюминия со скоростью 6,7 км/с по 1,5-мм пластинке из алюминия (интервал между кадрами – 15 мкс)

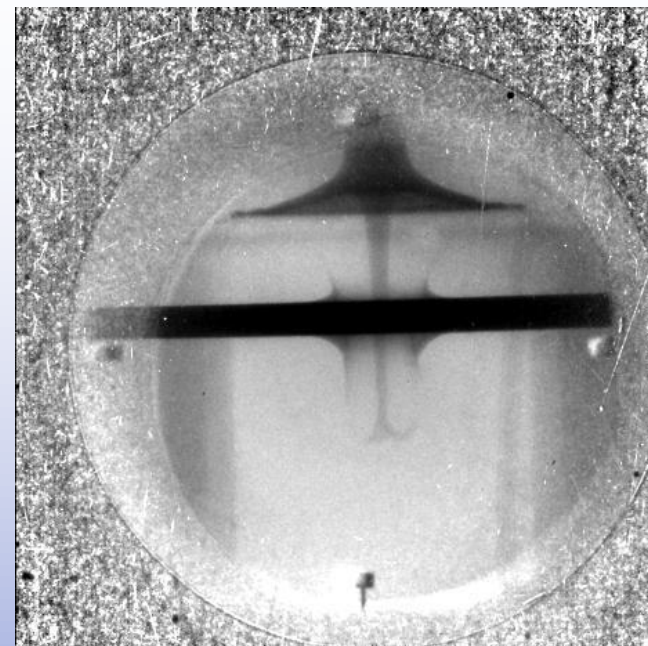
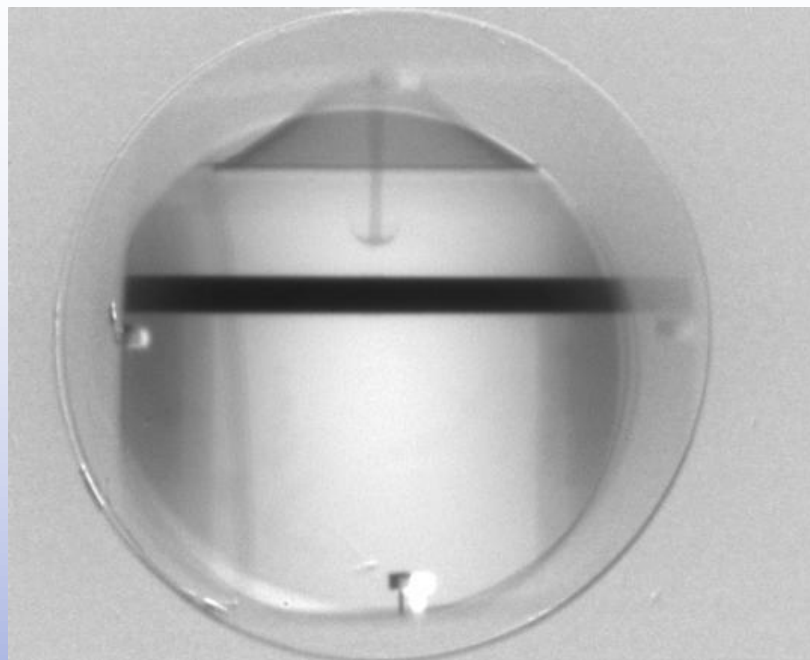
Современные методы исследования динамических процессов

- Контактные датчики.
- Современные реализации традиционных методов генерации рентгеновского излучения.
- Velocity Interferometer System for Any Reflector (VISAR).
- Протонография.
- Методы диагностики синхротронным излучением.
- По импульсной энергетике взрыв и ускорители похожи.



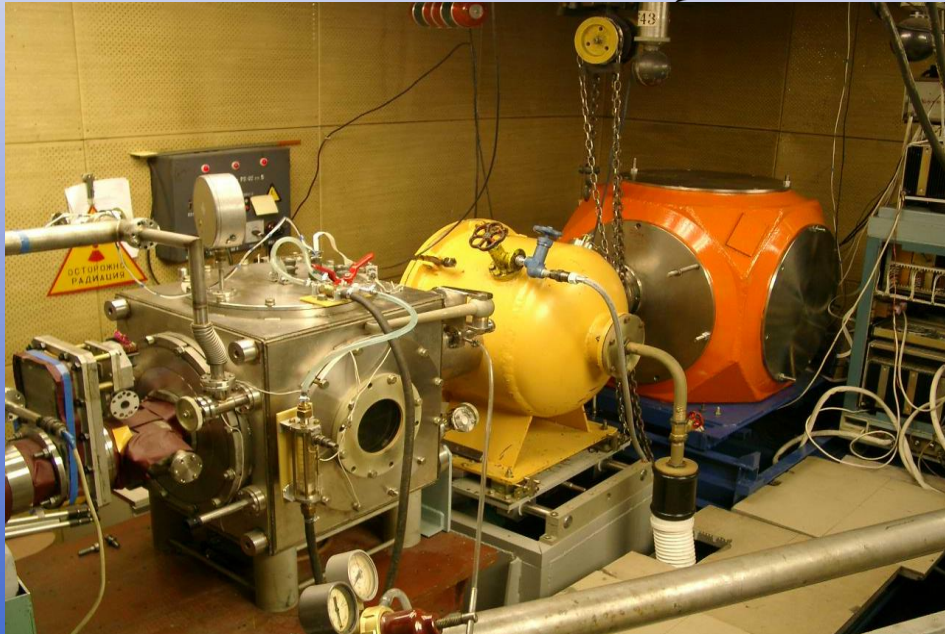
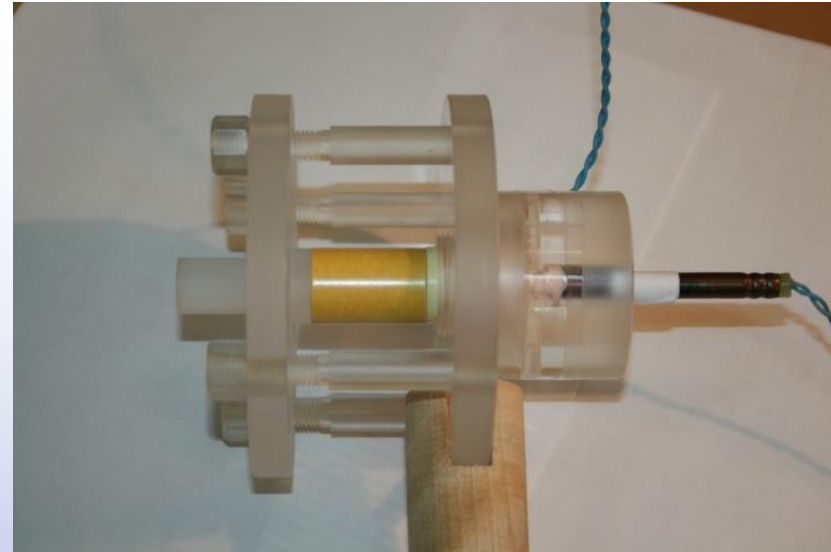
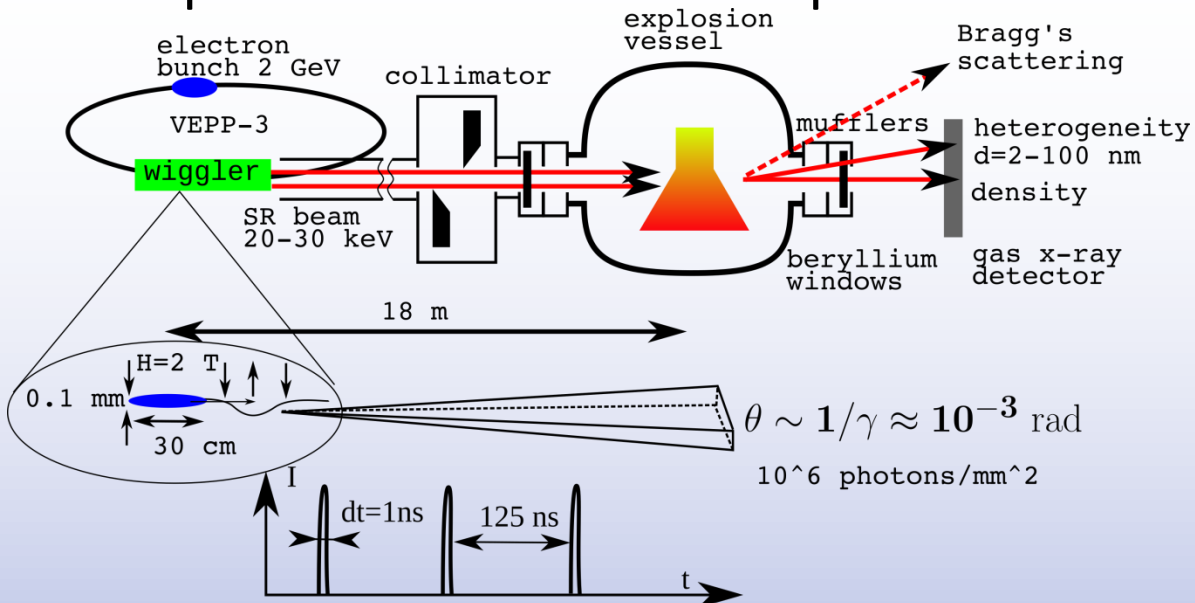
Центры по исследованию динамических процессов пучками различной природы.

Протонография динамических процессов



Протонная радиографическая установка на 70 ГэВ ускорителе ГНЦ ИФВЭ (г. Протвино). Установка позволяет получать изображение объектов с оптической толщиной свыше 300 г/см^2 . Оптическое разрешение установки составляет 0.25 мм .

Experimental scheme and photos of station on VEPP3/VEPP4

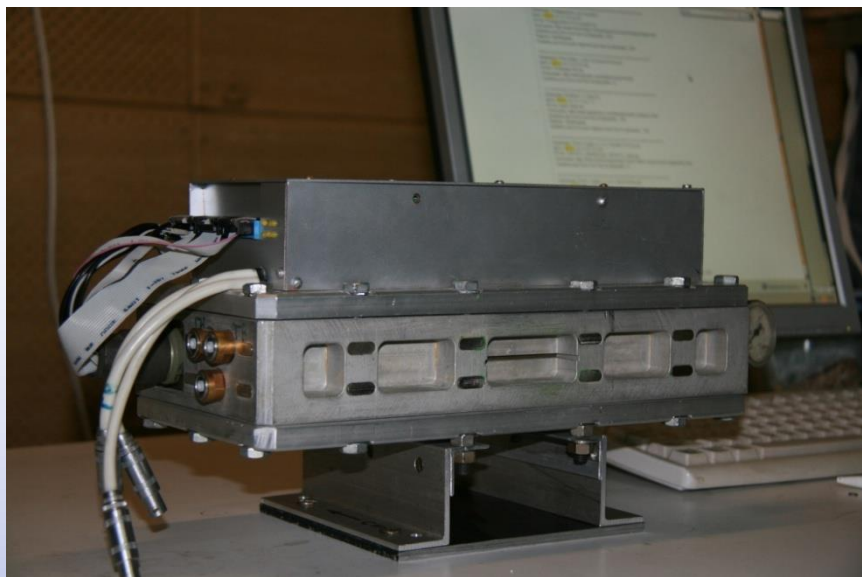


1999 r. Explosive mass 20 g. Time per frame 500 ns (today 125 ns). $E_{ef} = 20$ keV.

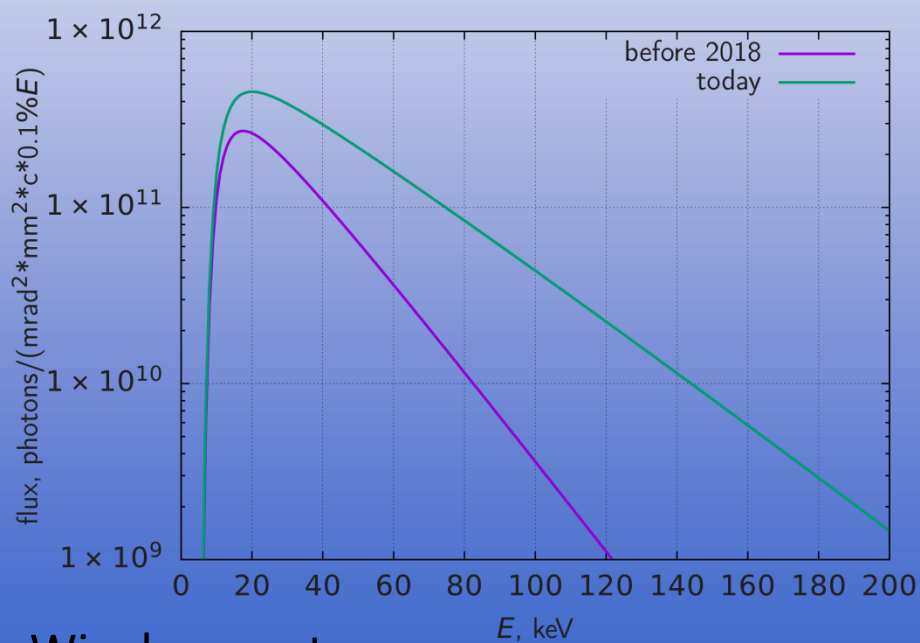


2013 r. Explosive mass 200 g. Time per frame 600 ns. $E_{ef} = 40$ keV.

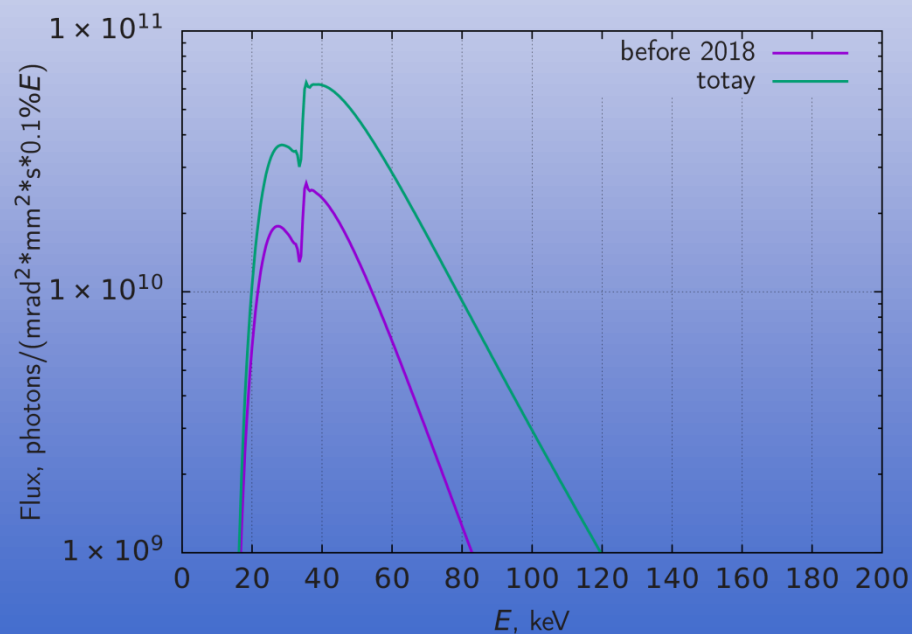
Microstrip gase detector for imaging of fast processes (DIMEX)



Характеристики детектора DIMEX-3.
Рабочий газ 70%Xe+30%CO₂,
Шаг стрипов 100 мкм,
Число пространственных каналов 512,
Число временных кадров 100,
Минимальное время между кадрами is 125 ns.
Динамический диапазон 10²-10³.
10⁴ фотонов в канал, за банч.

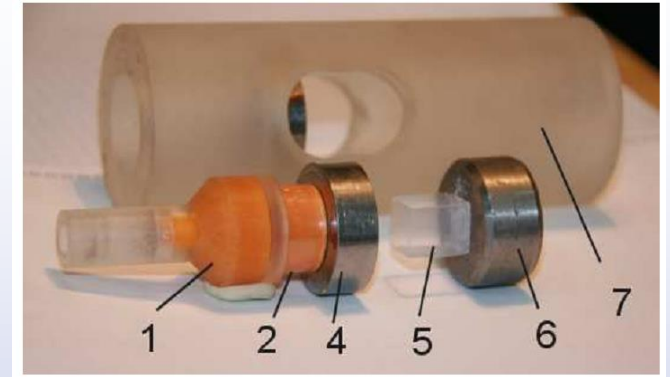
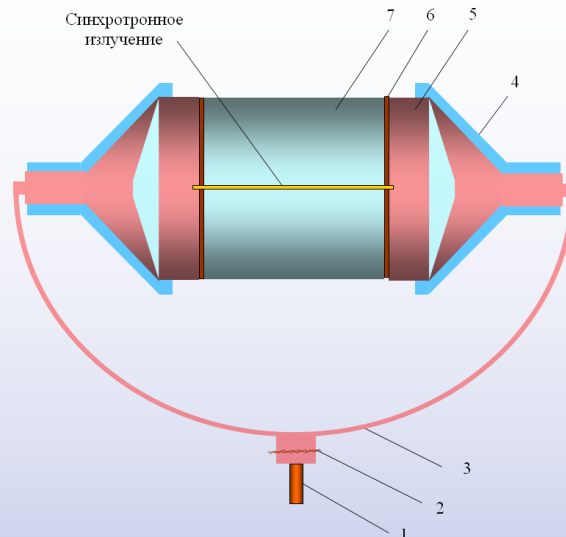
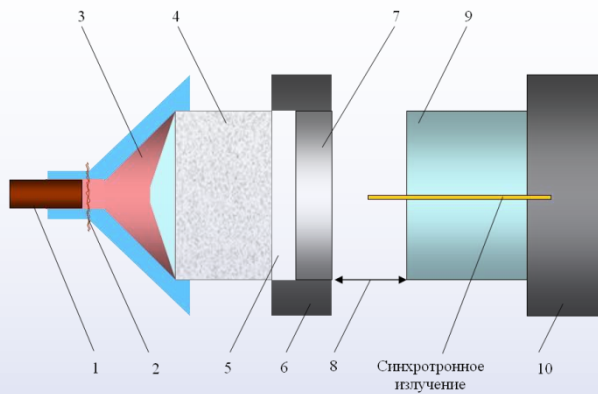


Wiggler spectrum.

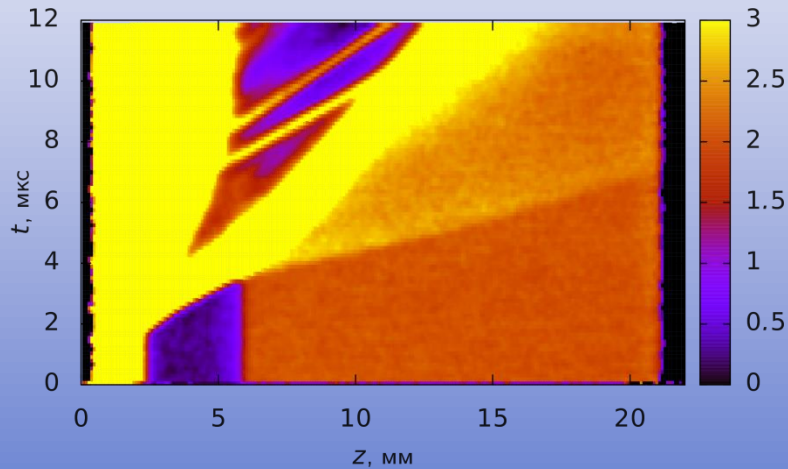


Final effectivity (wiggler, sample and detector).

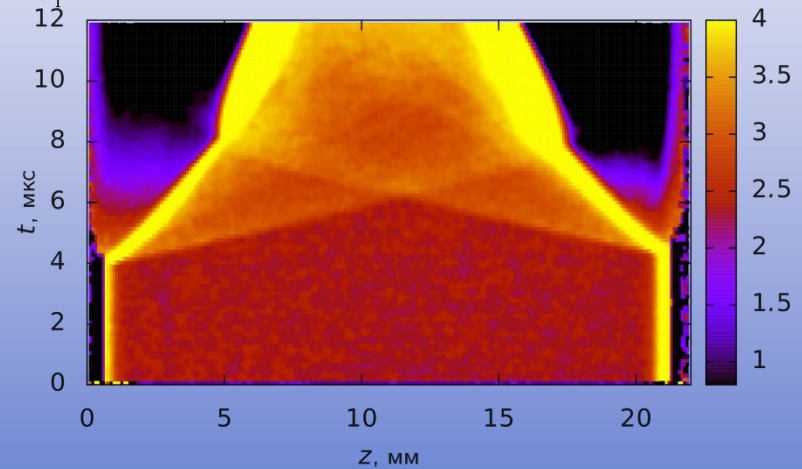
Shock wave experiments



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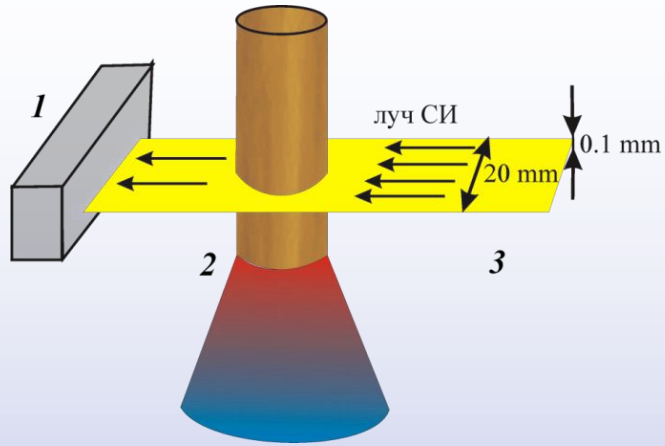


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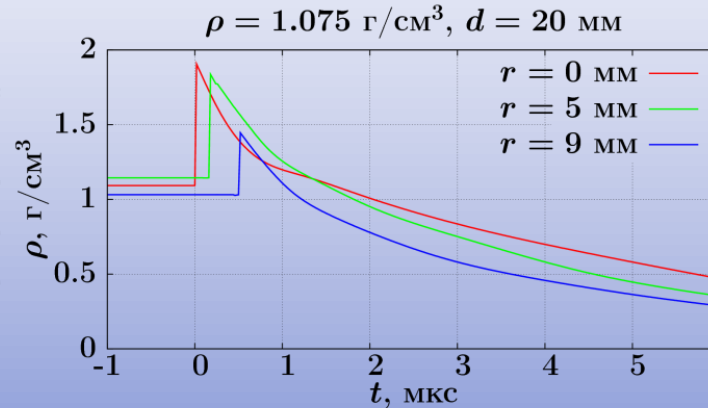
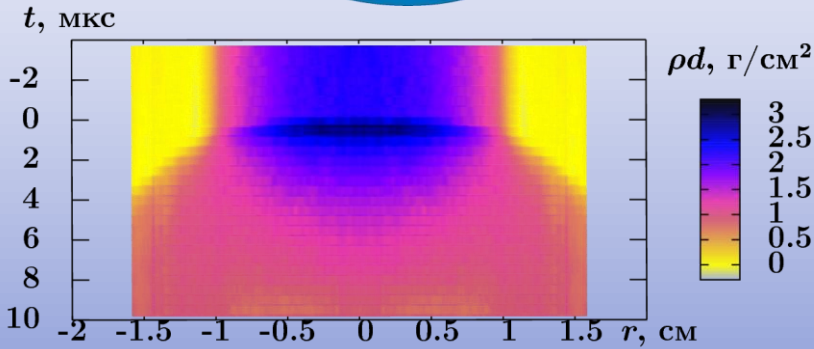


Shock wave investigation: 1 – explosive lens, 2 – main charge, 4 – guard ring with a thrown metal drummer (1 - 3 km/s), 5 - tested sample (0.1 - 2 g/cm³), 6 - base, 7 - centering guide.

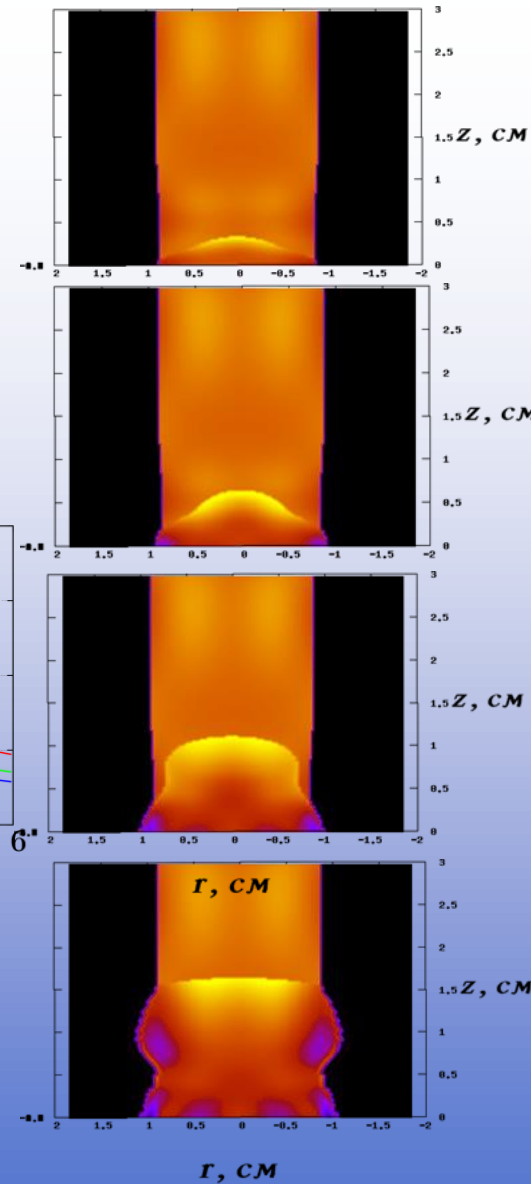
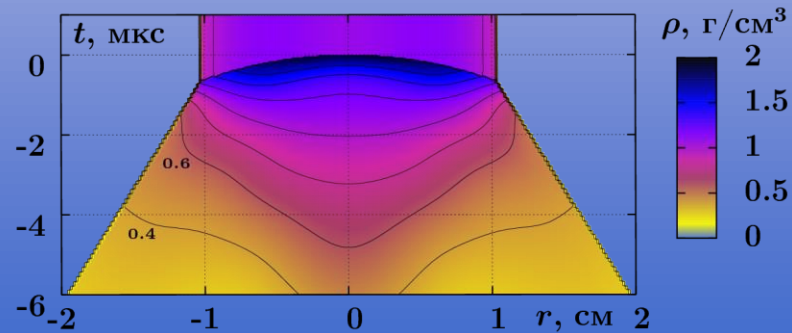
High speed x-ray tomography



Scheme of tomography experiment for density distribution reconstruction: 1 – detector for transmitted and attenuated x-ray radiation, 2 – investigated cylindrical sample, 3 – x-ray beam.



Detonation of emulsion explosive. X-ray shadow and density distribution.



Combustion to detonation transition in charge of porous petn. Density distribution at 2, 3, 4, 5 mks from initiation time.

Restoration of gas-dynamic flow parameters: density, pressure and mass velocity

Equations of gas dynamics for a flow with cylindrical symmetry

$$\frac{\partial r\rho u}{\partial r} + \frac{\partial r\rho v}{\partial z} = \frac{\partial r\rho}{\partial t},$$

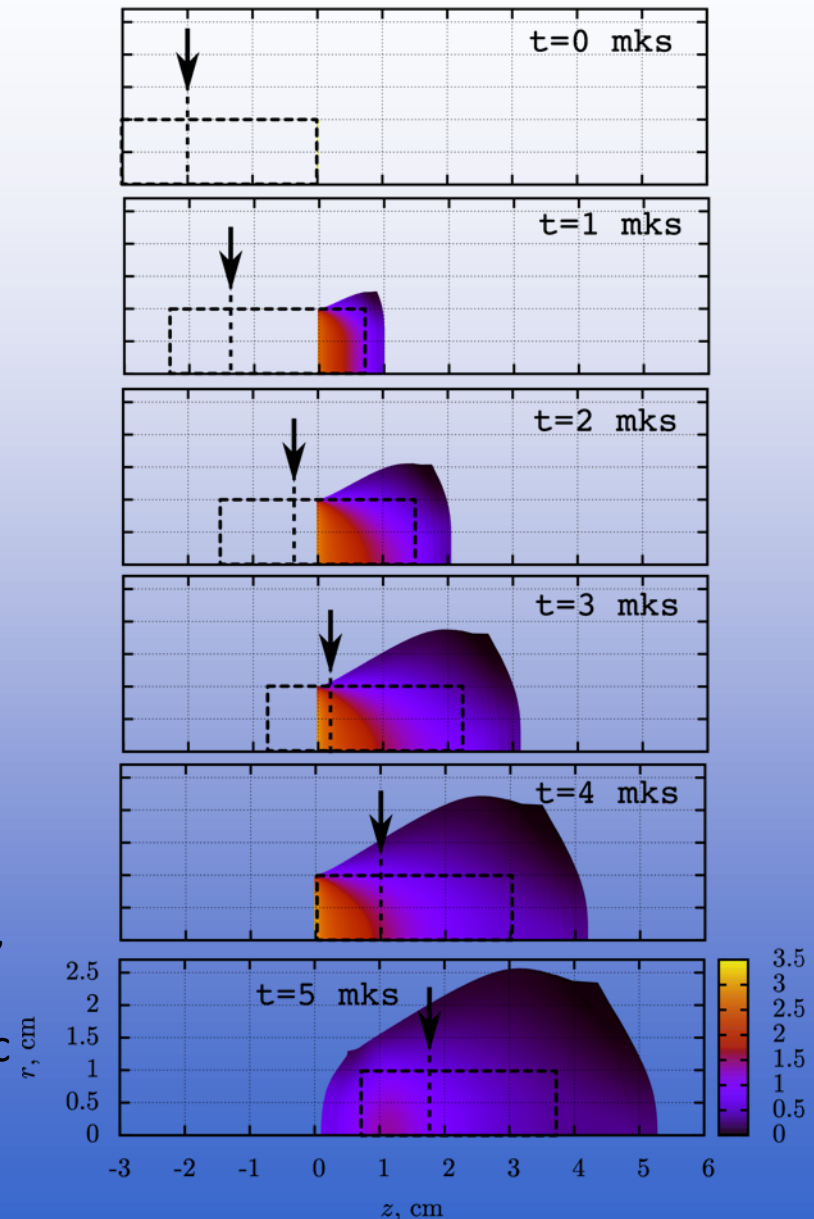
$$\frac{\partial r\rho u^2}{\partial r} + \frac{\partial r\rho uv}{\partial z} + r\frac{\partial p}{\partial r} = \frac{\partial r\rho u}{\partial t},$$

$$\frac{\partial r\rho v^2}{\partial z} + \frac{\partial r\rho uv}{\partial r} + r\frac{\partial p}{\partial z} = \frac{\partial r\rho v}{\partial t},$$

$$p(\rho) = p_0(\rho/\rho_{00})^{\gamma(\rho)}.$$

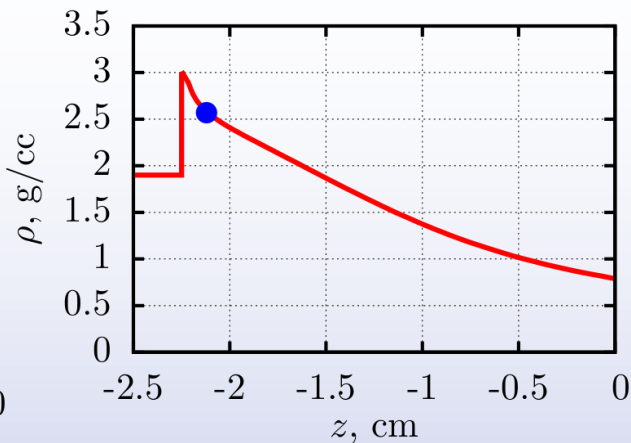
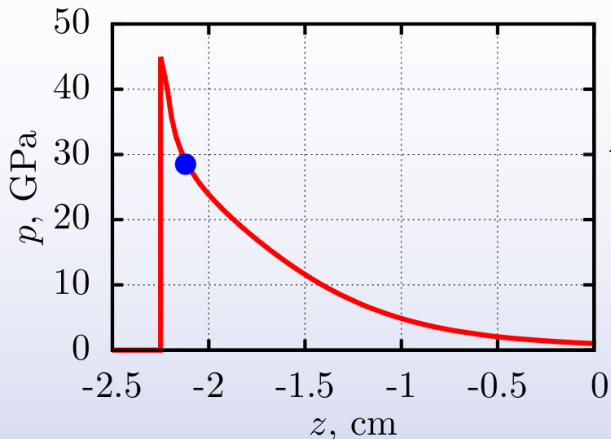
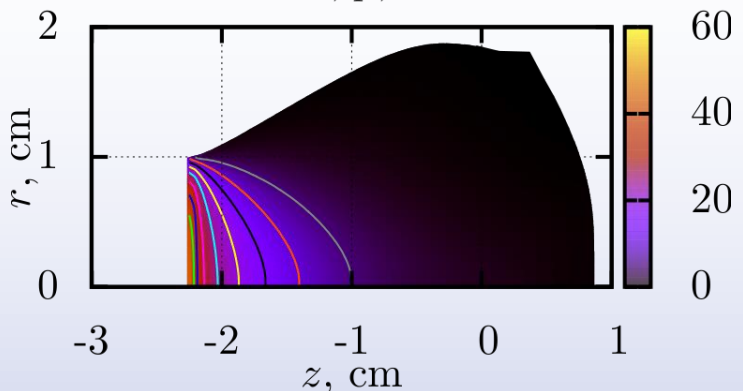
$\gamma(\rho)$ - the required dependence of the adiabatic exponent along the streamline.

The problem is solved numerically by the Godunov method, in Lagrange coordinates, the discontinuity decays were considered in the acoustic approximation. The characteristic number of "adjustable" parameters 10, the characteristic number of flow computations 10^3 - 10^4 .

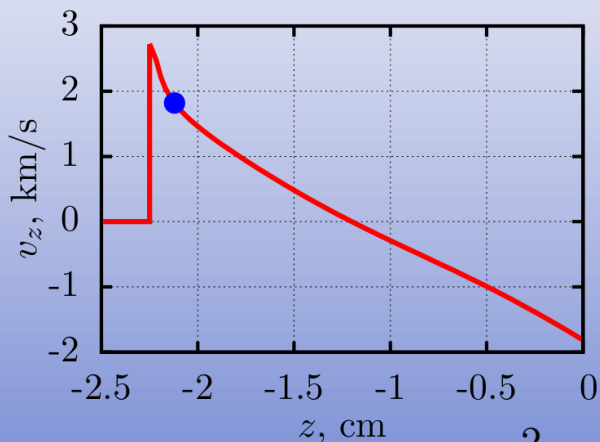
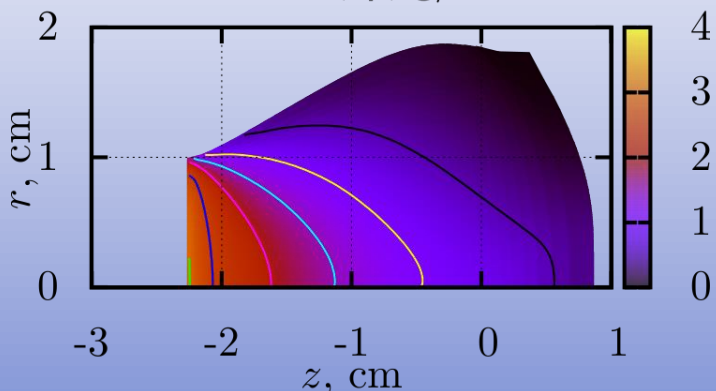


Parameters of the flow during detonation of the charge of the TATB

TATB, p , GPa



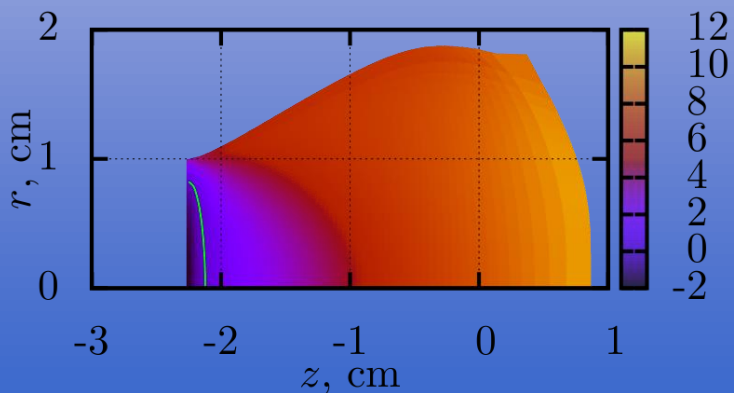
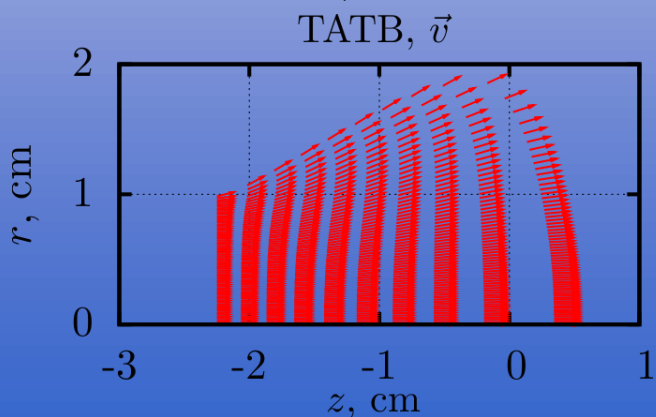
TATB, ρ , g/cc



$$p(\rho)$$

$$c = (\partial p / \partial \rho)^{1/2}$$

TATB $v_z - c$, km/s



X-ray scattering and Detonation synthesis of carbon nanostructures

In the detonation products of a number of explosives, condensed carbon particles with a diverse phase composition are formed:

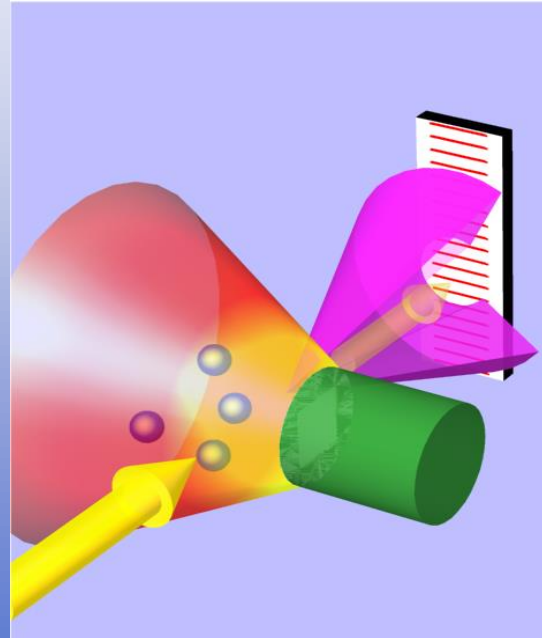
$C_7H_5N_3O_6$ – trinitrotolol (tnt)

$C_3H_6N_6O_6$ – hexogen (rdx)

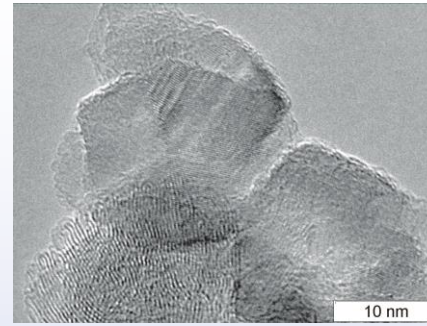
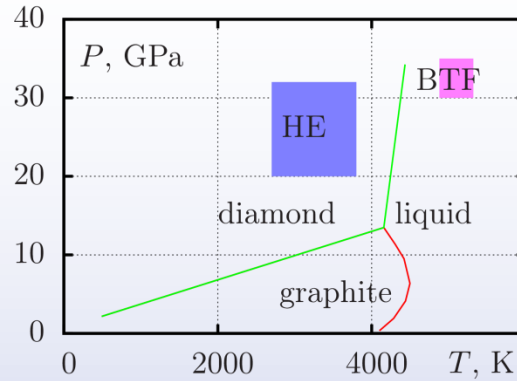
$C_6H_6N_6O_6$ – trimino trinitrobenzene (tatb)

$C_6N_6O_6$ – benzotrifuroxane (btf).

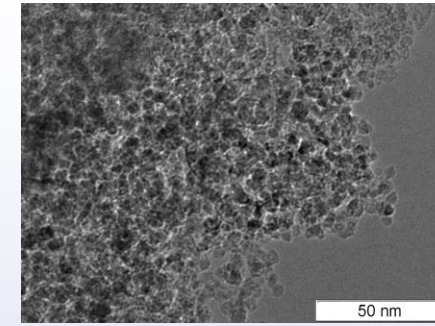
Yellow arrow - incident beam of SI,
violet cone - X-ray scattering on carbon nanoparticles.



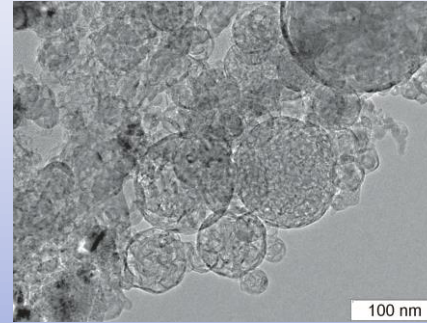
The method of small-angle X-ray scattering allows determining the parameters of the emerging particles in dynamics: B – tnt/rdx 70/30, C – tnt/rdx 50/50, D - tnt, E - tnt/rdx 60/40, F - rdx.



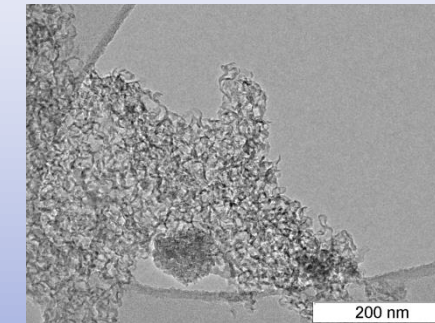
tnt



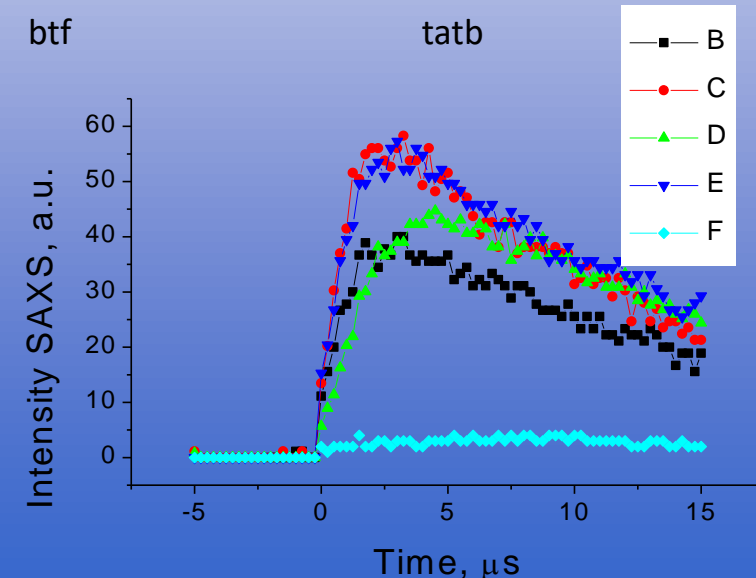
tnt + rdx (50/50)



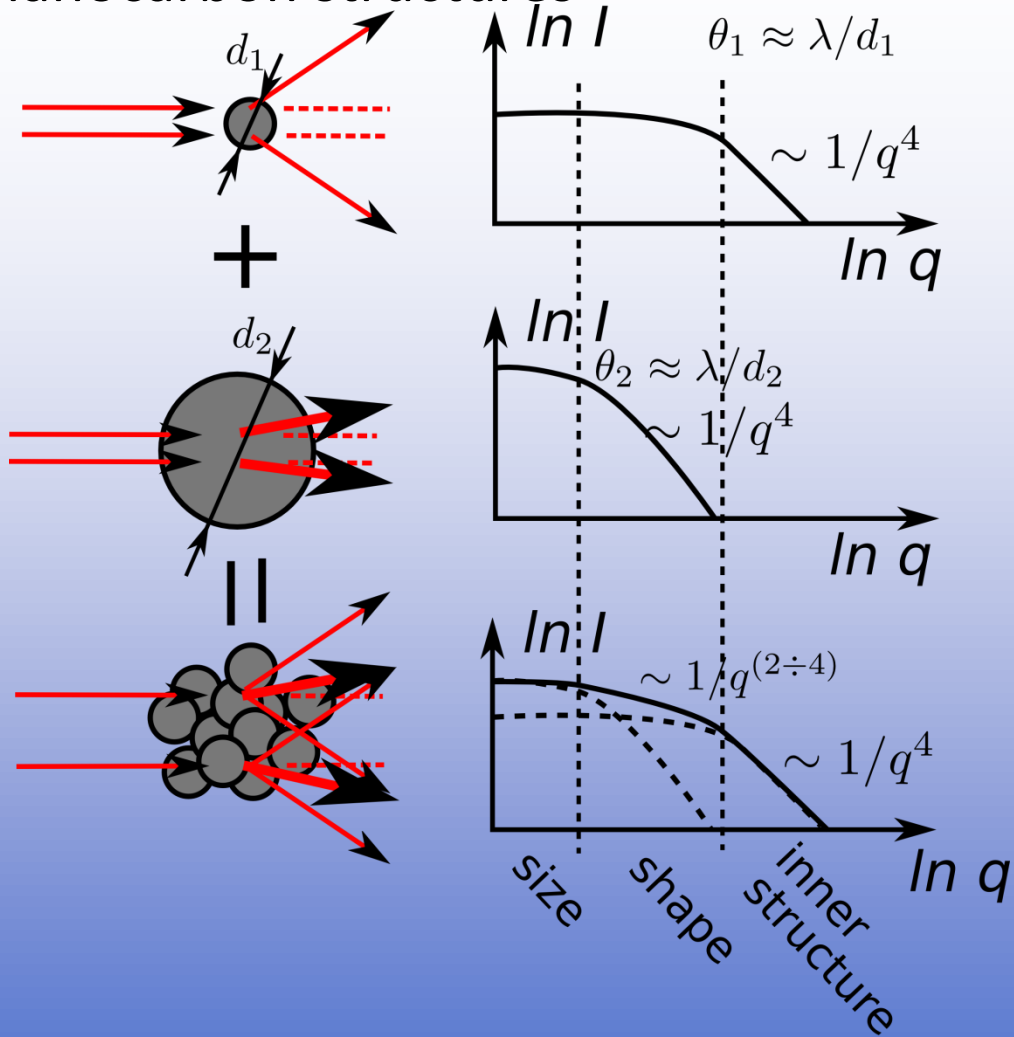
btf



tatb

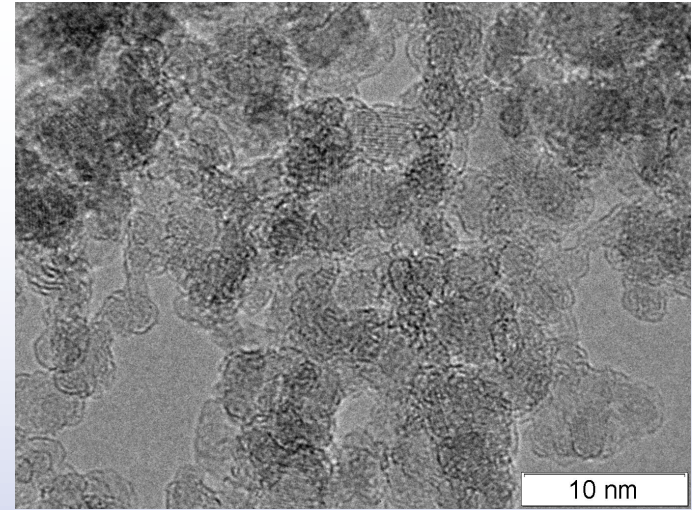


Reconstruction of the shape of nanocarbon structures

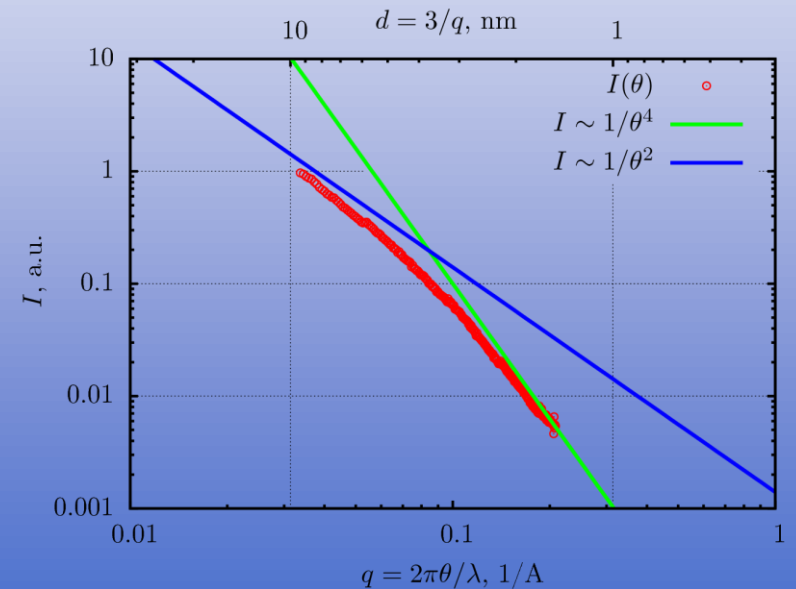


Simplified measurements

$$\theta \approx \lambda / d \quad I(\theta) \longleftrightarrow \Delta\rho(\text{scale} = \lambda / \theta)$$

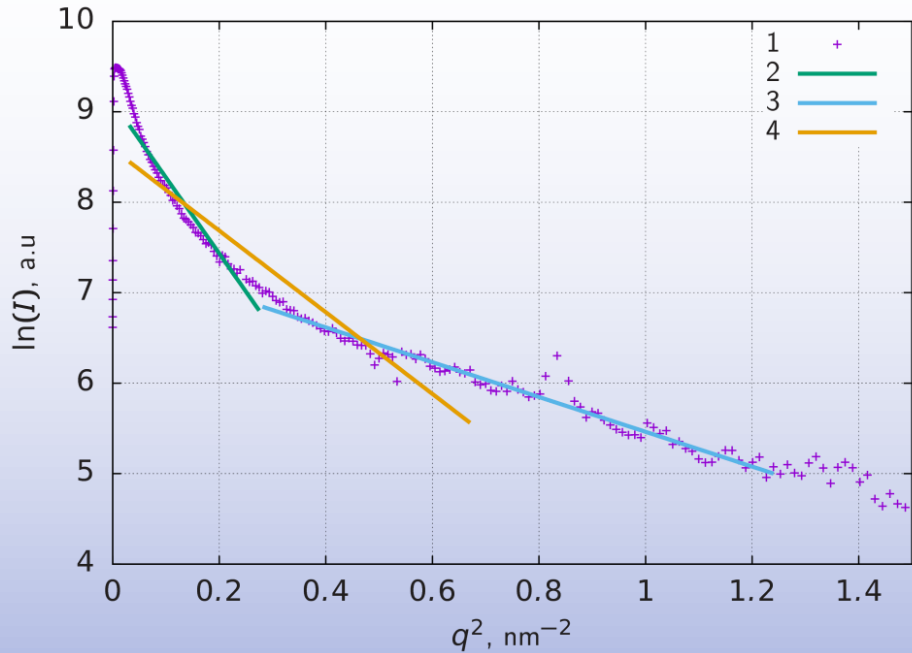


Detonation carbon.

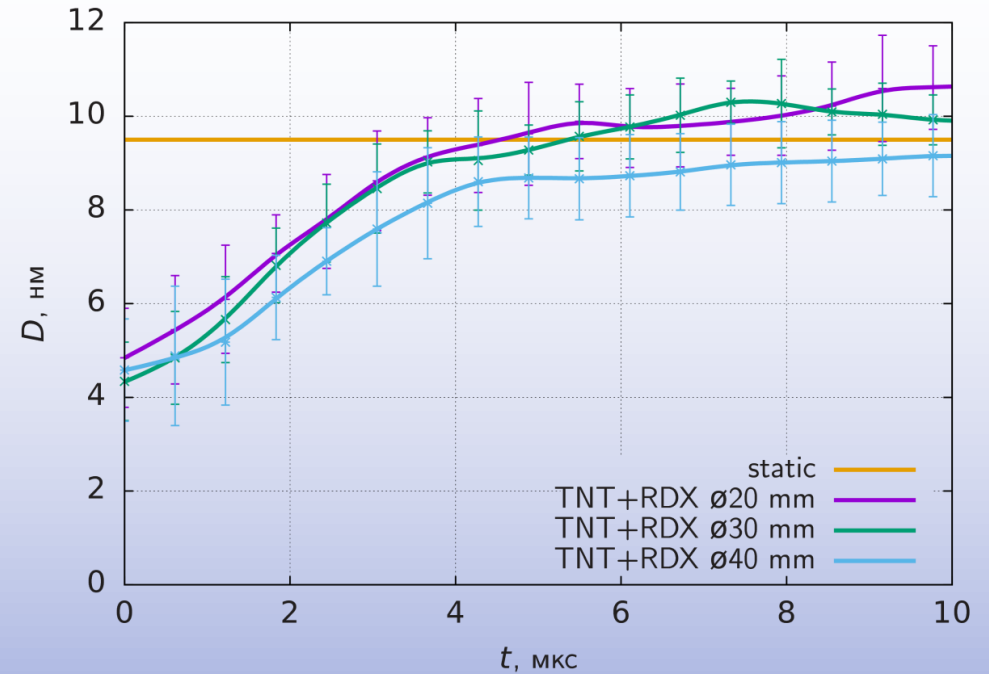


Static measurement of scattered x-ray from detonation carbon. Fractal structure and homogeneous particle.

Reconstruction of carbon particle size

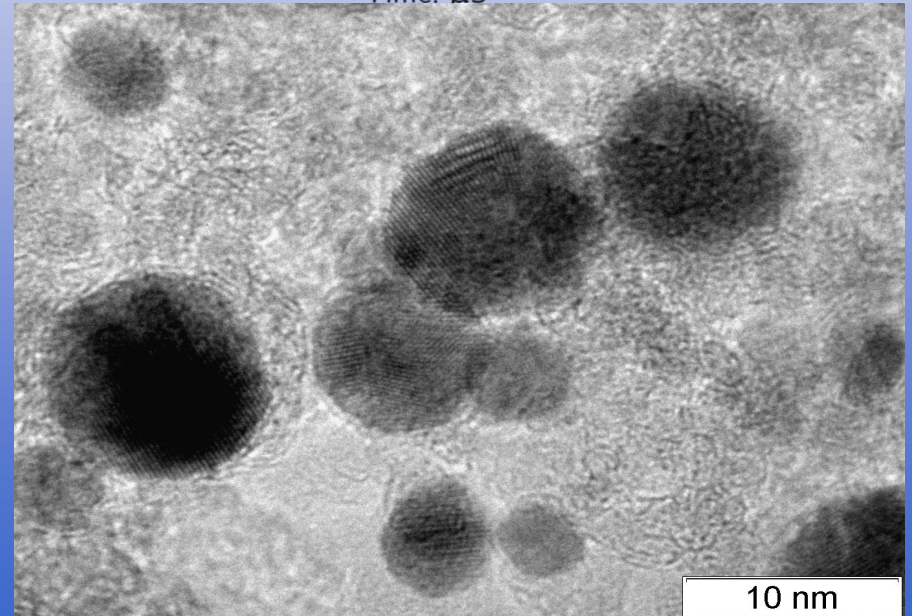
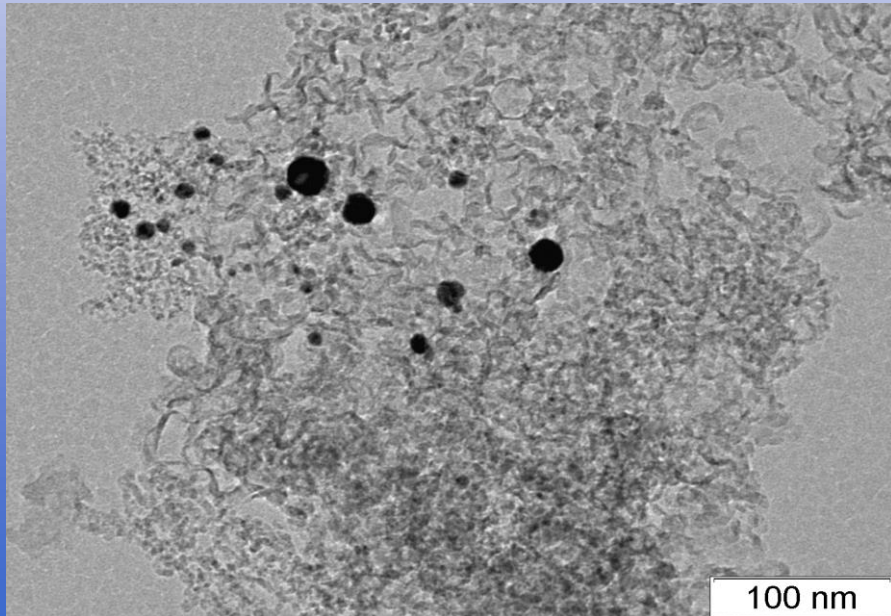
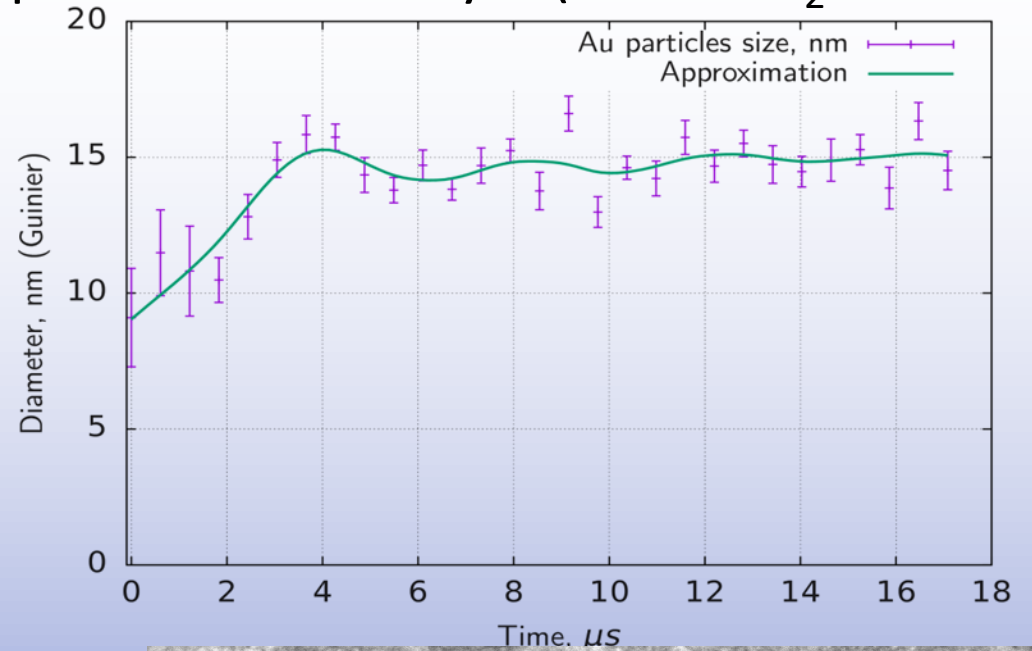


Static experiment. Guinier approximation for different scattering vector q ranges:
0.9-2.6 mrad $D=13$ nm;
0.9-4.1 mrad $D=9.5$ nm;
2.6-5.5 mrad $D=6.2$ nm.



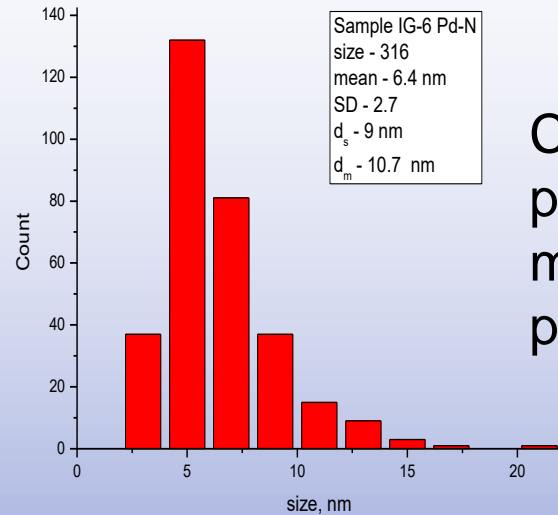
Dynamics experiment for cylindrical charges of explosive with different diameter.

Detonation synthesis of metal nanoparticles for catalysis(CO to CO₂ oxidation)



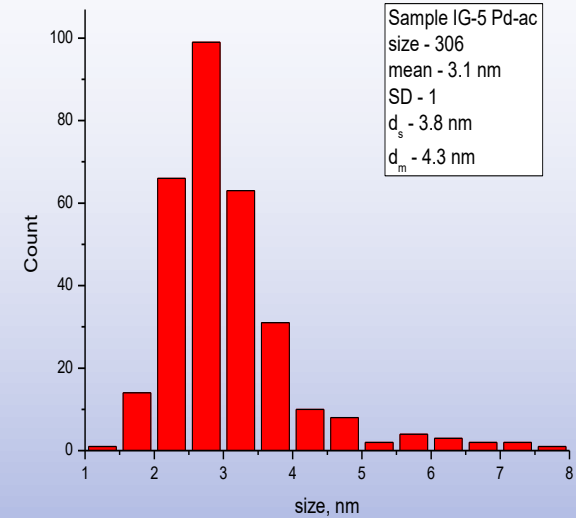
Particle size control

Palladium nitrate ($\text{Pd}(\text{NO}_3)_2$).
C/Pd=0, D = 6.4 nm.

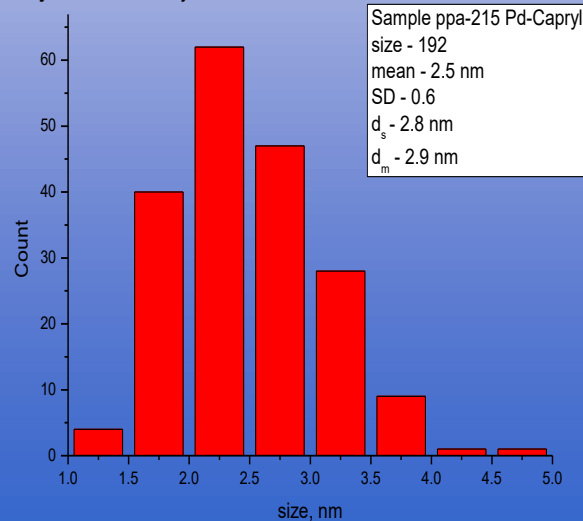


Compounds with a larger part of palladium in the molecule produce larger particles.

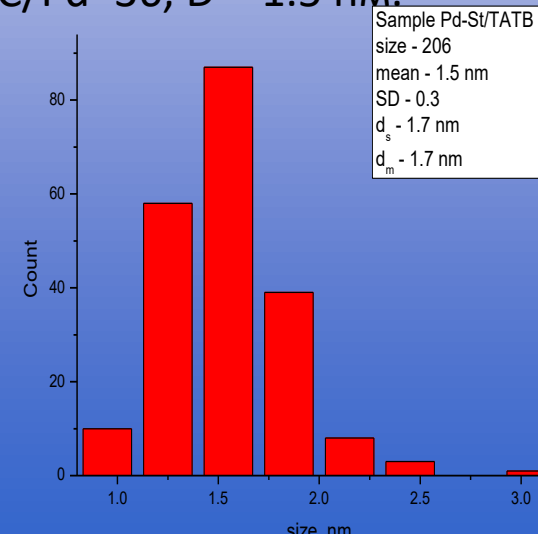
Palladium acetate ($\text{Pd}(\text{O}_2\text{CCH}_3)_2$).
C/Pd=4, D = 3.1 nm.



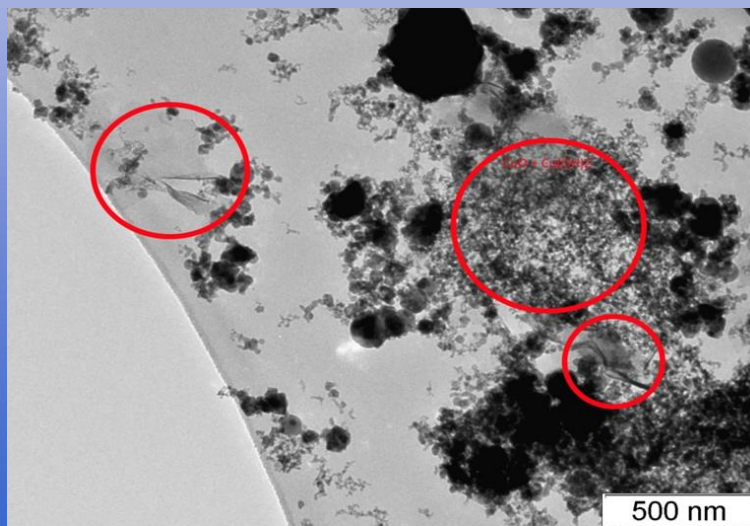
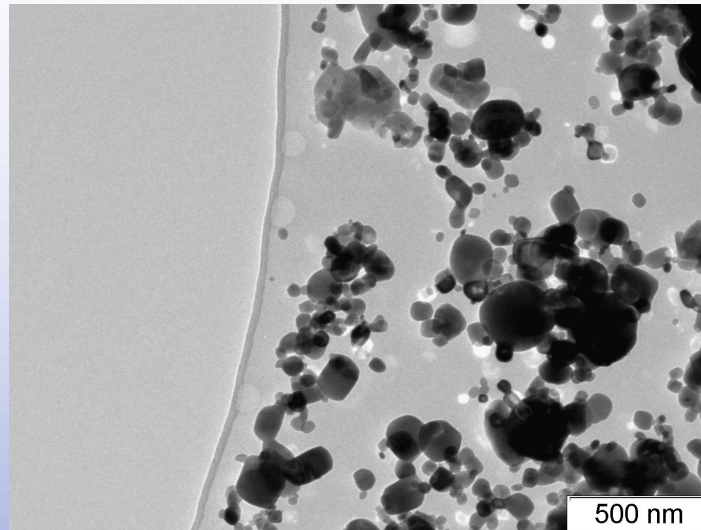
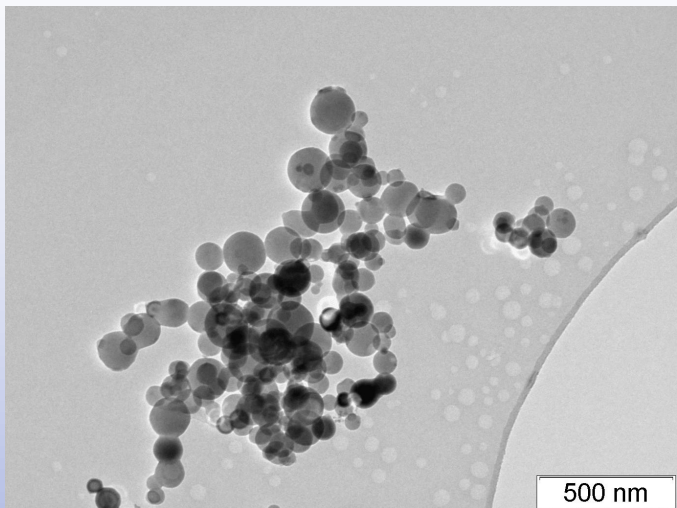
Palladium caprylate ($\text{Pd}(\text{C}_7\text{H}_{16}\text{COO})_2$).
C/Pd=16, D = 2.5 nm.



Palladium stearic ($\text{Pd}(\text{C}_{17}\text{H}_{35}\text{COO})_2$).
C/Pd=36, D = 1.5 nm.

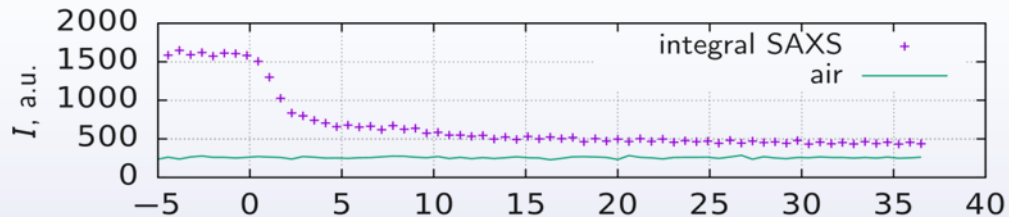


Combustion of nanothermic mixtures

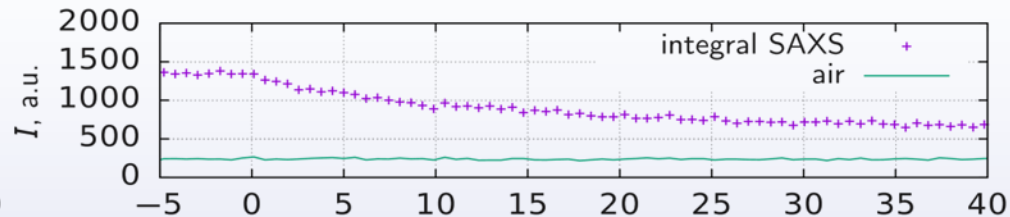


Scattering and density at thermite combustion

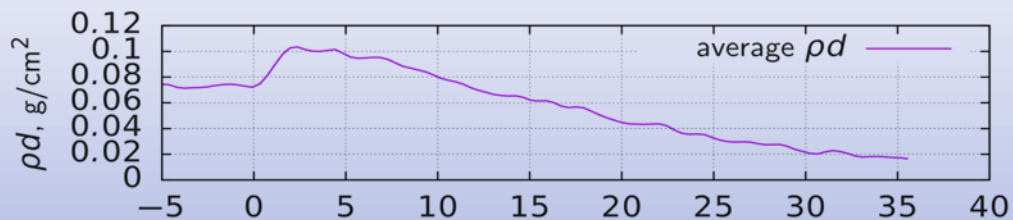
Nanothermite CuO/Al, $\rho = 0.5$ g/cc, front velocity 524 m/s



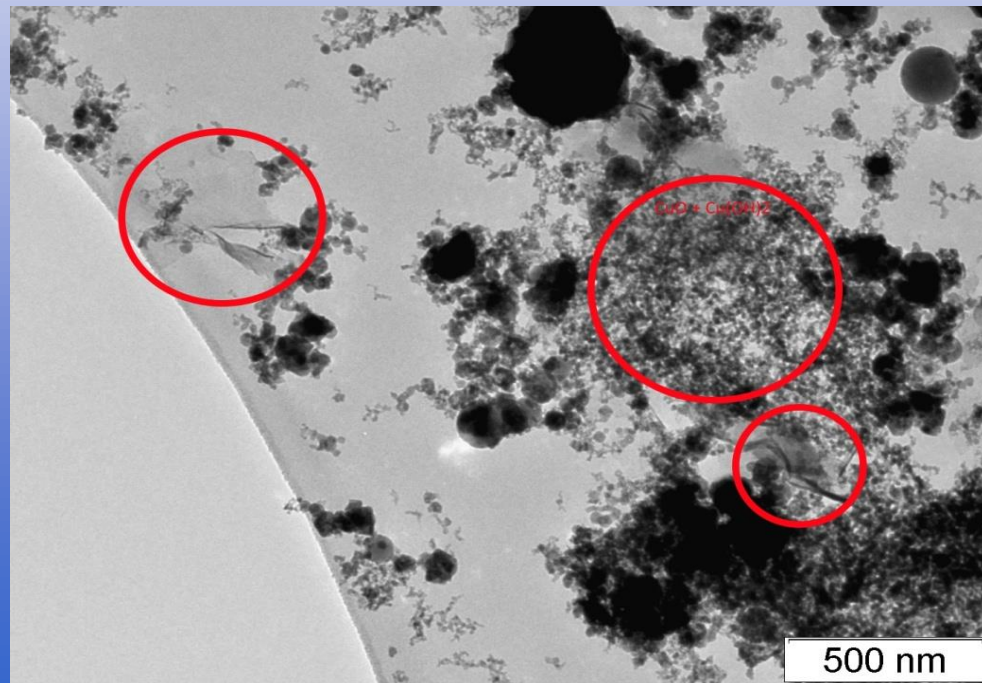
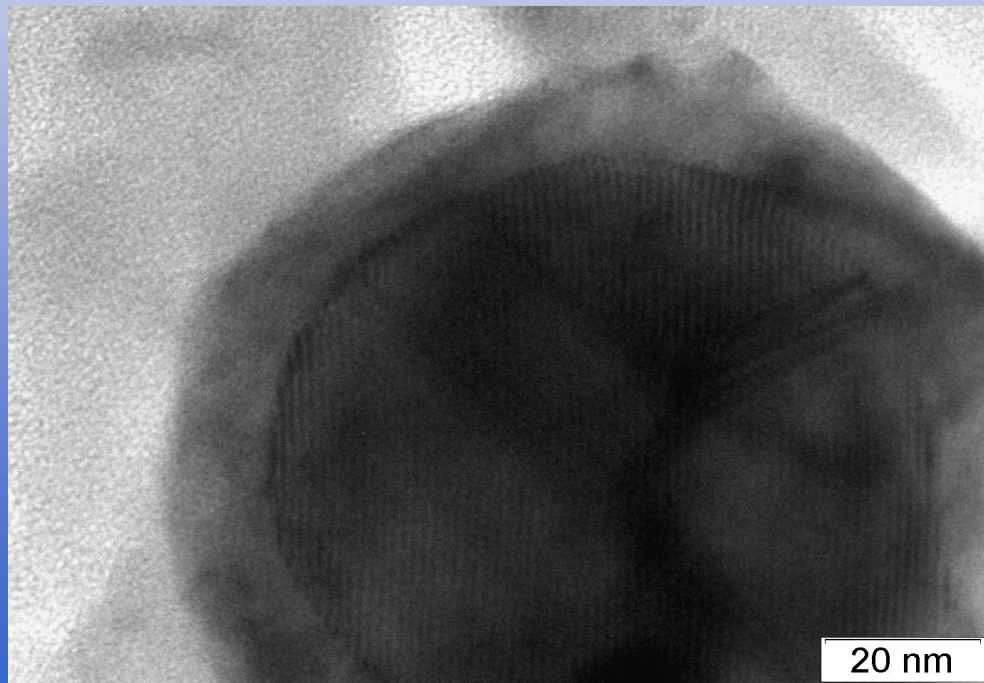
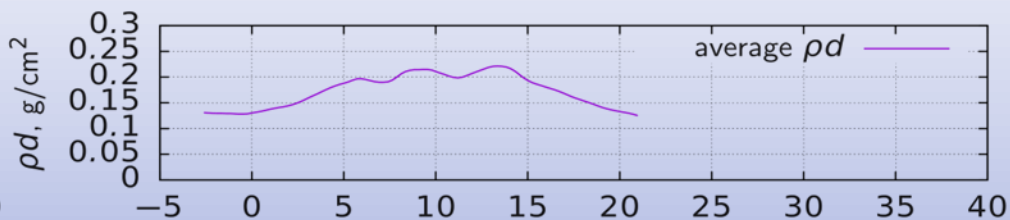
Nanothermite Al/CuO, $\rho = 1.1$ g/cc, Velocity 217 m/s



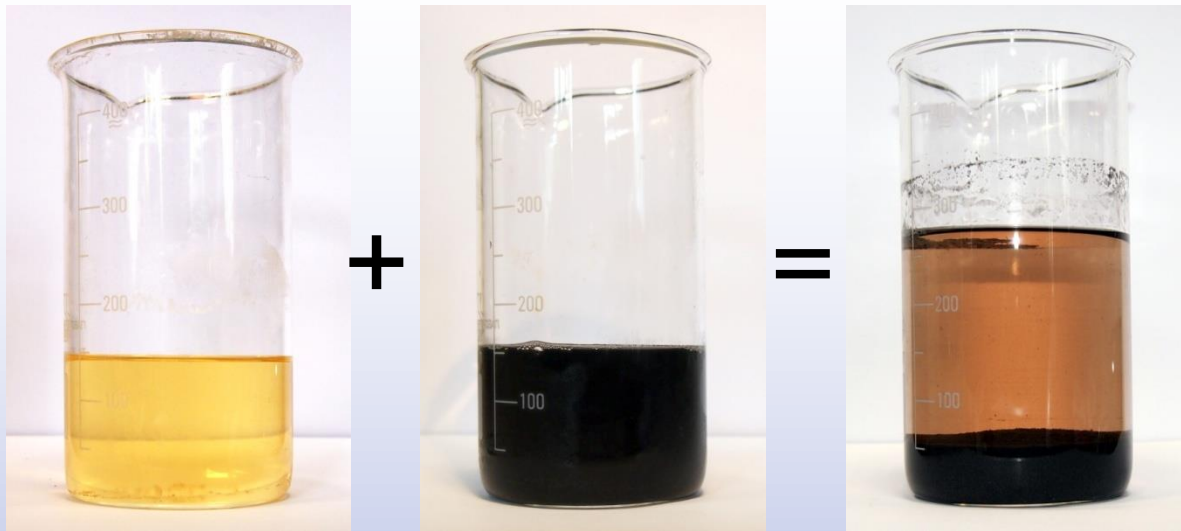
Nanothermite CuO/Al, $\rho = 0.5$ g/cc, front velocity 524 m/s



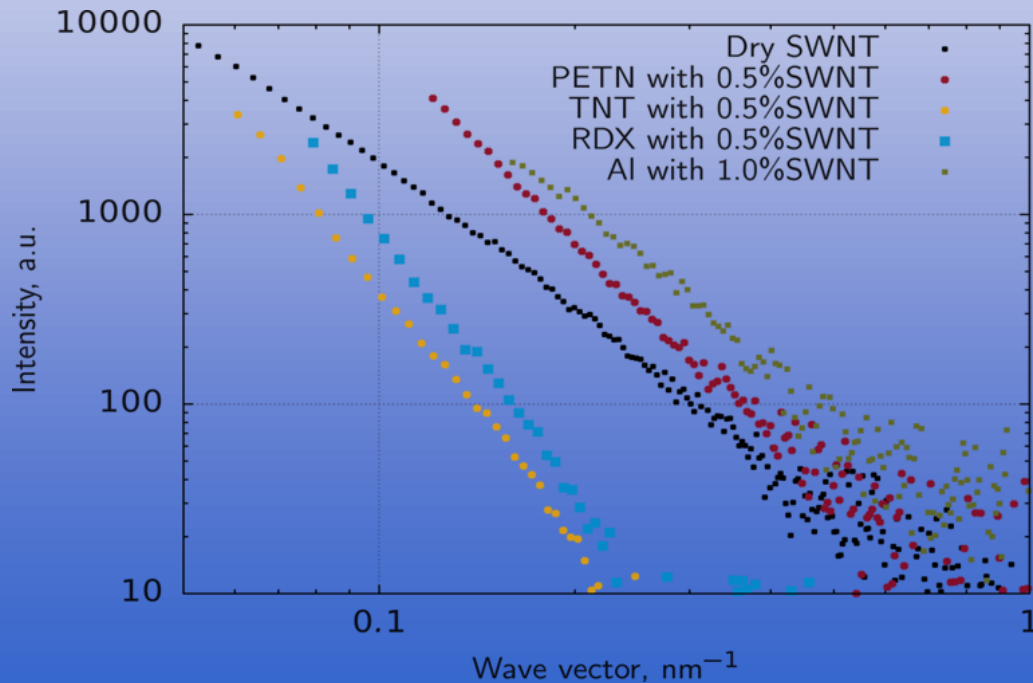
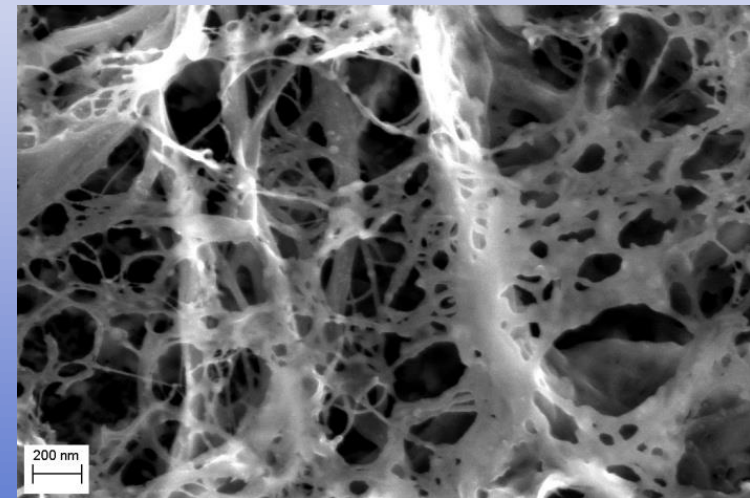
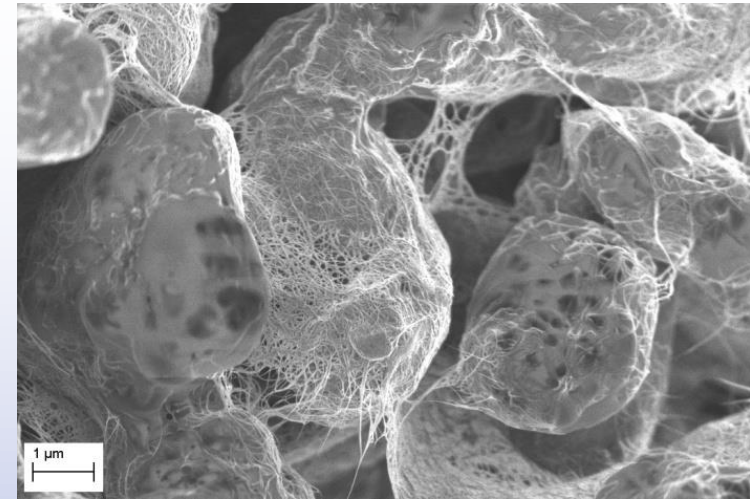
Nanothermite Al/CuO, $\rho = 1.1$ g/cc, Velocity 217 m/s



Modification of explosives by carbon nanotubes

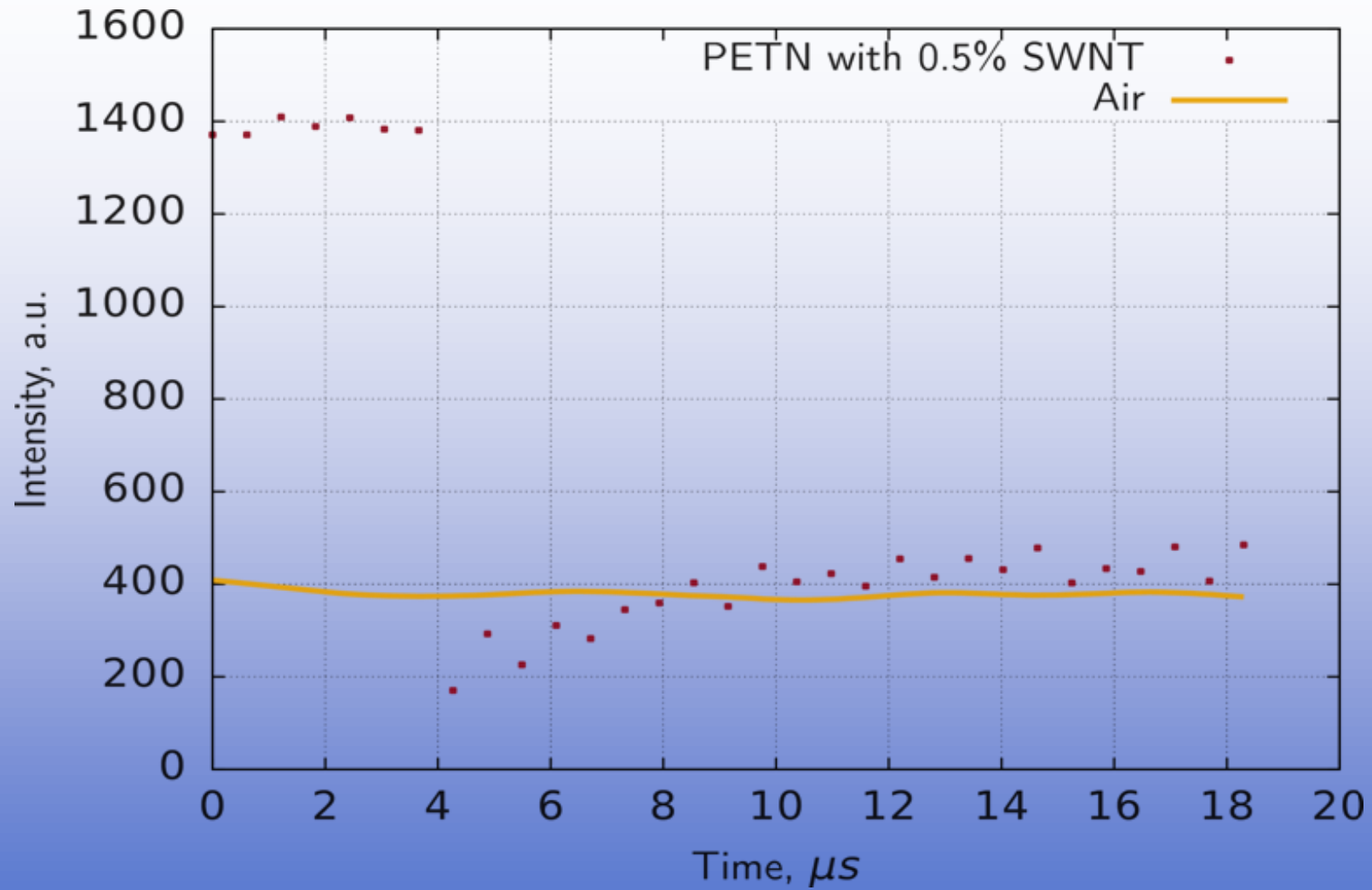


A solution of TNT in acetone. + Carbon nanotubes dispersed in water = Nanostructured explosive.

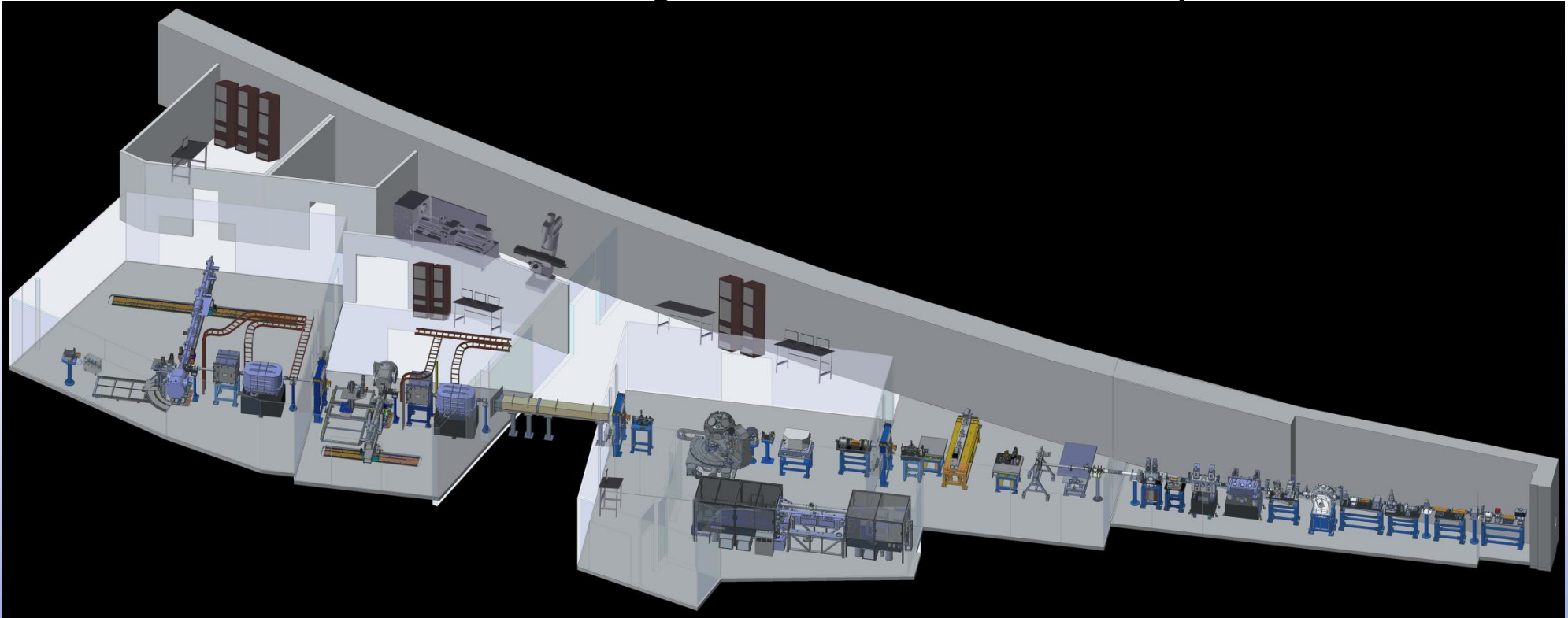


Nanostructured explosive.

X-ray scattering at detonation. Petn with single wall carbon nanotube.



Advanced Photon Source, Argonne National Laboratory



DCS experimental and beamline characteristics include:

- Peak stresses: to well over 350 Gpa.

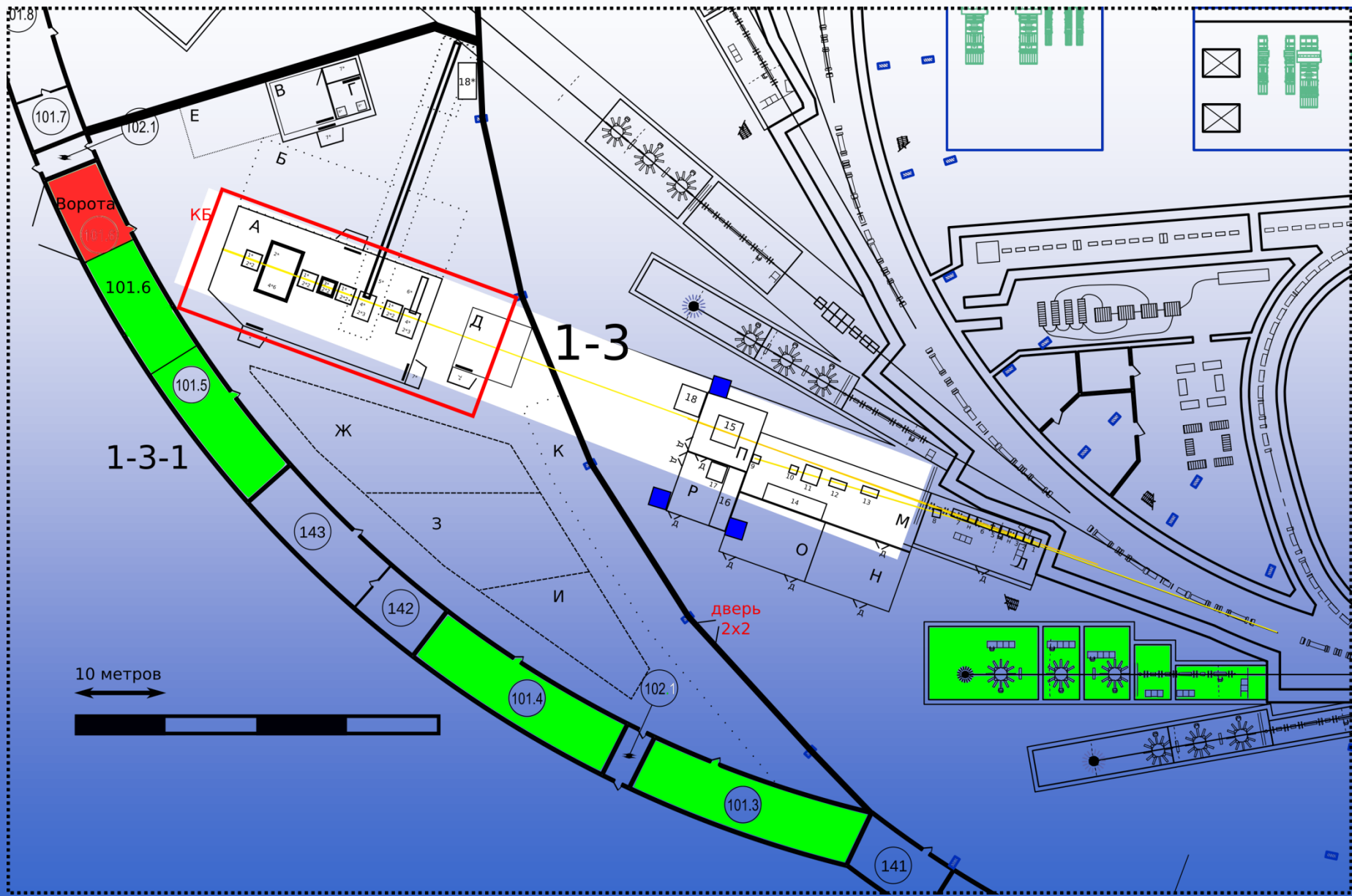
- Shock wave time durations: ~5 ns to microsecond.

- Focus on diffraction, imaging, and scattering measurements; simultaneous continuum measurements.

- Energy range from 5-35 keV – with energies to 100 keV for imaging.

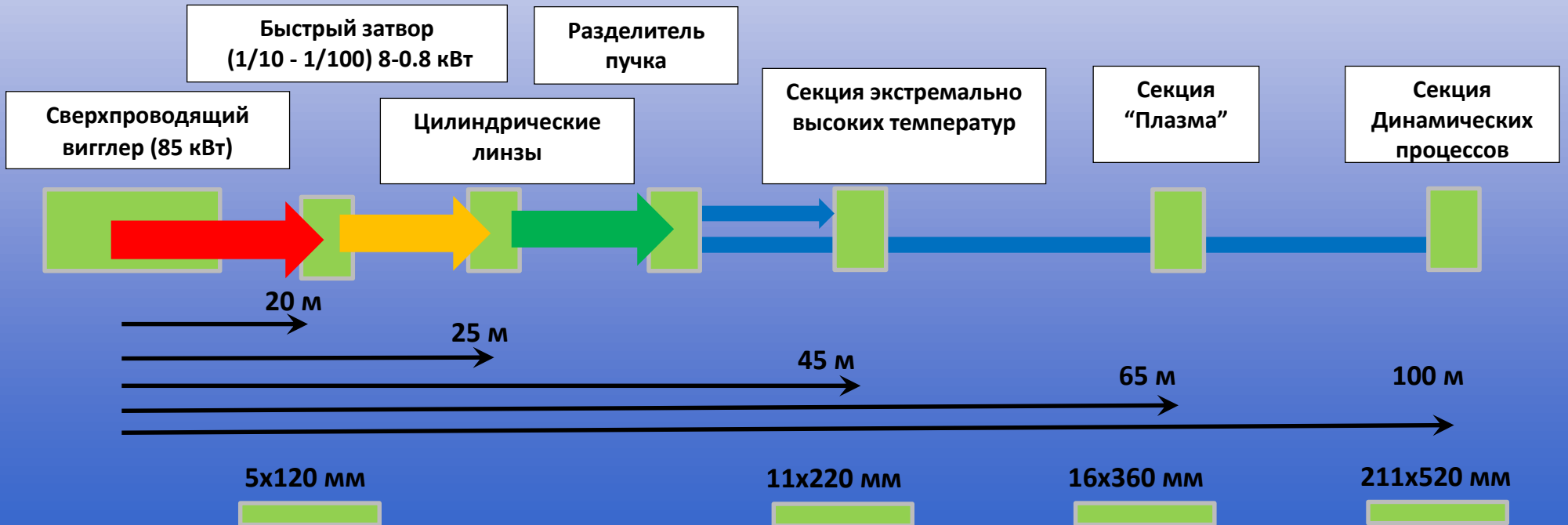
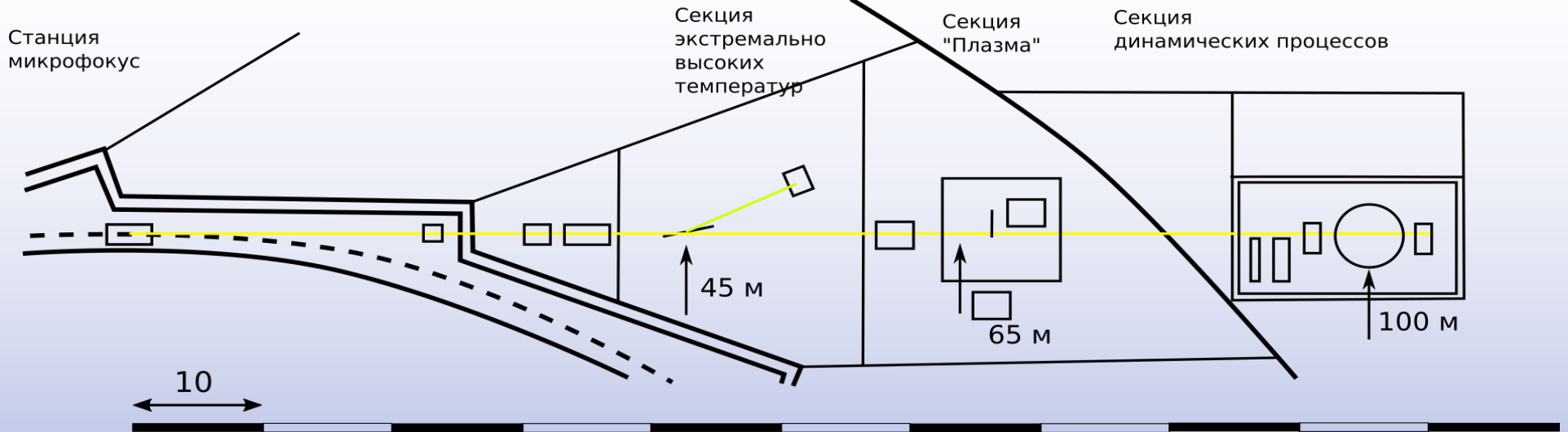
- Special purpose experiments to complement dynamic compression.





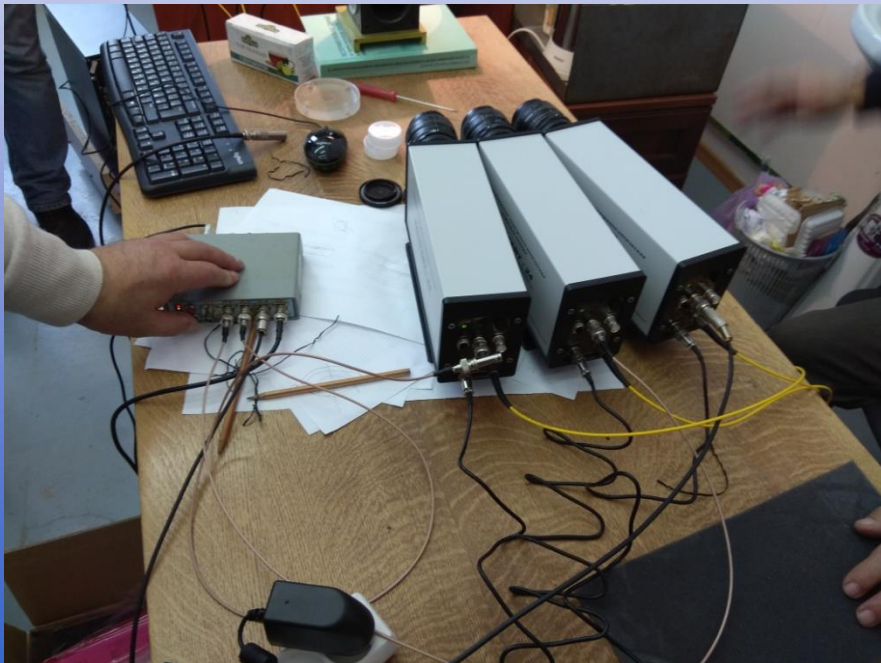
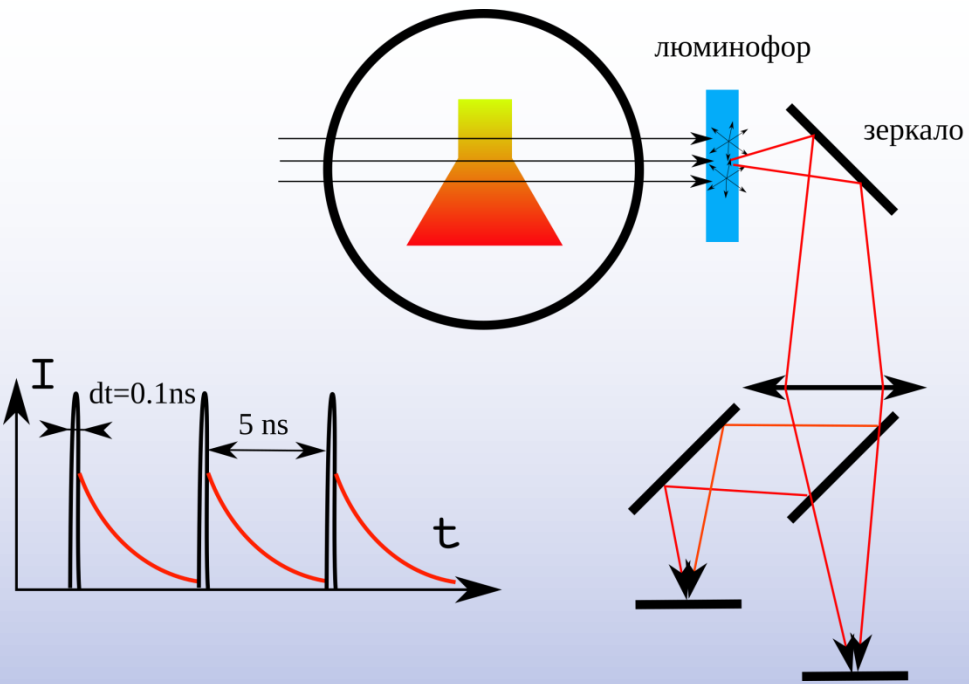
Общая схема станции

Станция исследования быстропротекающих процессов



Требования к пучку СИ на секциях станции

Время между банчами	Распределение по периметру	Заряд в банче	Полный ток в накопителе
5-6 нс	Равномерное заполнение	2.48 нК (12 нК ВЭППЗ)	0.4 мА (≈ 255 банчей)
100 нс	Равномерное заполнение	45 нК	0.4 мА (≈ 14 банчей)
5-6 нс	Поезд (train)	20 нК	0.4 мА (≈ 30 банчей) $5.5 * 30 = 165$ нс $T = 1591$ нс





*Thank you
for your attention!*

*Благодарю
за внимание!*