NEW X-RAY SOURCE FOR MEDICAL APPLICATIONS BASED ON CHANNELING RADIATION AND POLYCAPILLARY OPTICS

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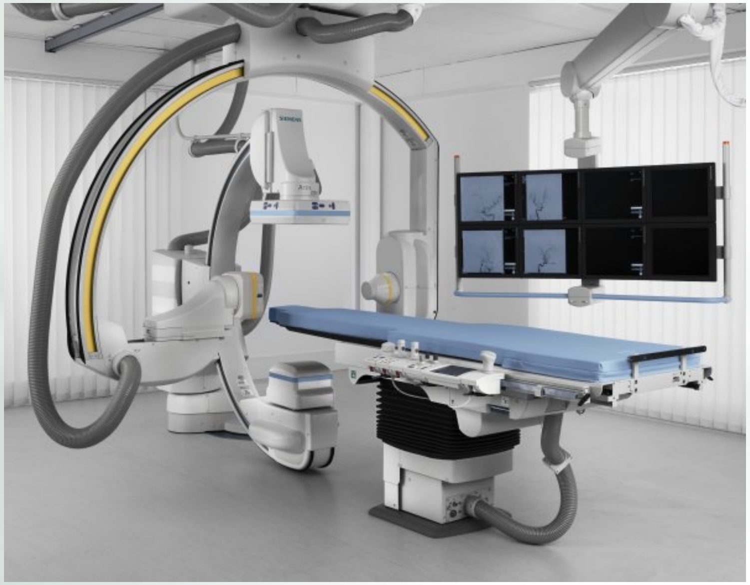
REQUIREMENTS FOR X-RAY RADIATION SOURCES

The required photon energy:

- 15 keV for mammography,
- 100-120 keV for chest radiography,
- 33 keV for angiography (the key energy to get the iodine contrast; minimal photon flux is of $I \approx 10^4$ photons/(mm^2·shot), or a total intensity of $I \approx 10^9$ photons/s).

Irradiated area varying from 50x50 to 400x400 mm^2 for all these procedures.



Angiography facility

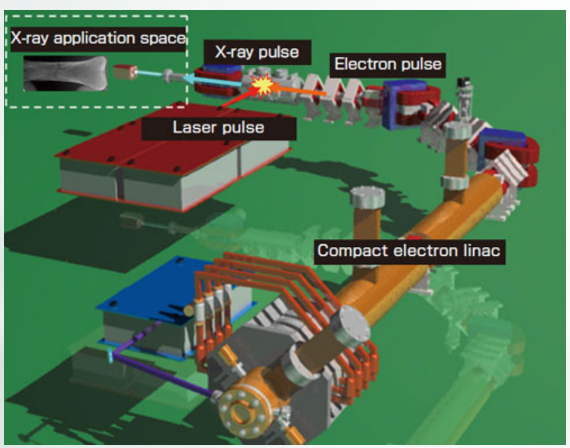
Conventional X-ray tube

MONOCHROMATIC X-RAY SOURCES

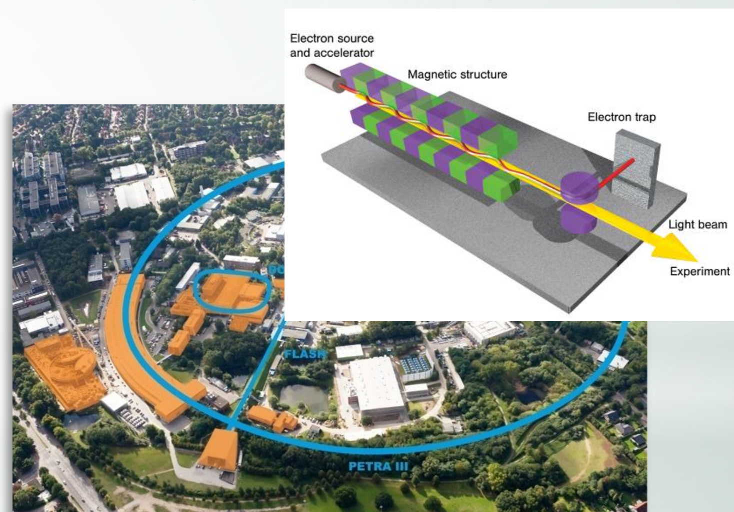
Quasi-monochromatic X-rays cannot be produced using conventional high-voltage X-ray tubes.

The other ways to produce monochromatic X-rays:

- Synchrotron radiation,
- Undulator radiation (X-ray FEL),
- Compton scattering,
- K-capture,
- Radiations in crystals (coherent bremsstrahlung, channeling radiation, parametric X-ray radiation, etc.)

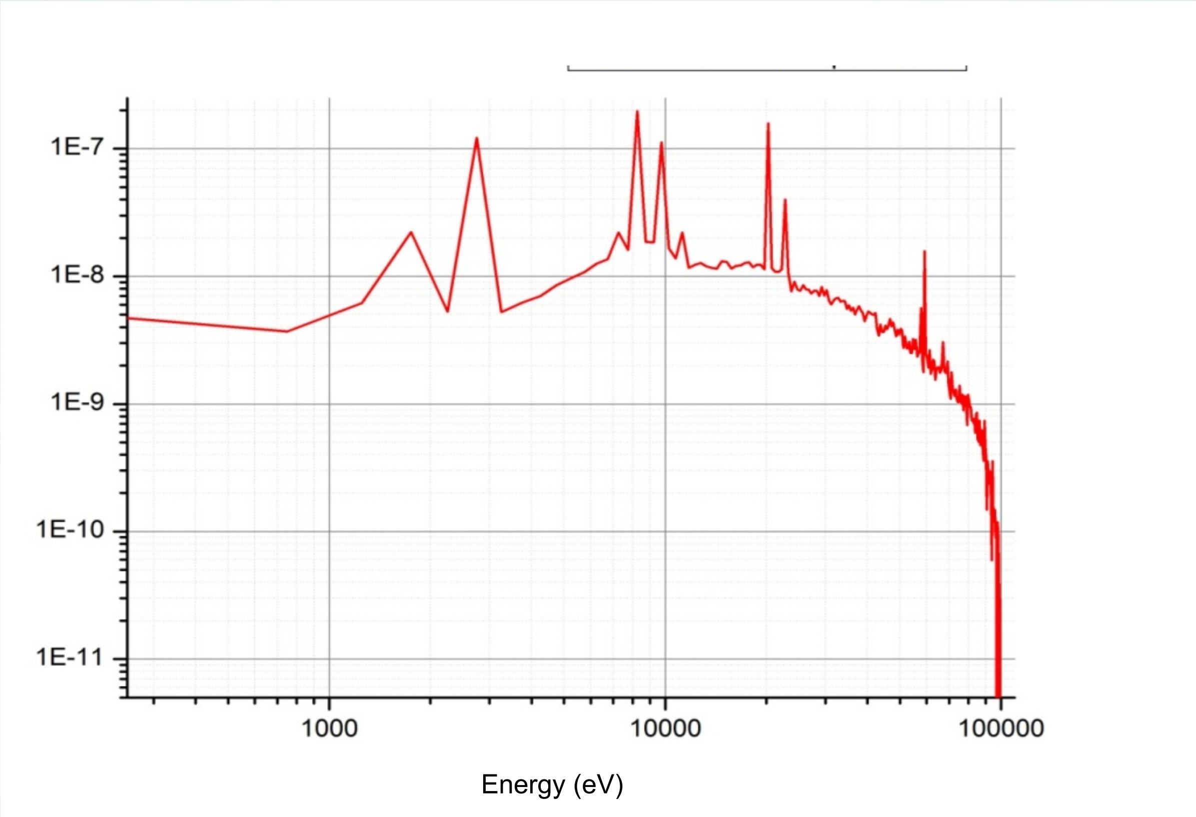


AIST (Compton scattering)



X-FEL (undulator)

X-RAY TUBE



Photon density distribution for 100 keV X-ray tube with W&Re anode

Photons with energy < 15 keV are absorbed in body => the low-energy tail is harmful

Solution: different filters.

However, all using filters are effective for 17 keV (good for mammography), and are not effective at > 33 keV (for contrast imaging, like angiography etc).

MONOCHROMATIC X-RAY SOURCES

Alternatives					
Name	Stage	Photons energy, keV	Spectrum	Facility size	Price or Cost
Conventional X-ray tube	Market	10-150	Broad	Compact	0.1-2 ME
Radiography with synchrotron or undulator	Development (experiment)	Unlimited	Narrow	Very large	200-250 ME
Compton scattering	Development	10-60	Narrow	Large	3-6 ME
K-capture	Development	20 (Mo) – 80 (Au)	No	?	?
Channeling radiation + Polycapillary optics	Development	10-40, tunable	Narrow	Middle	2-3 ME

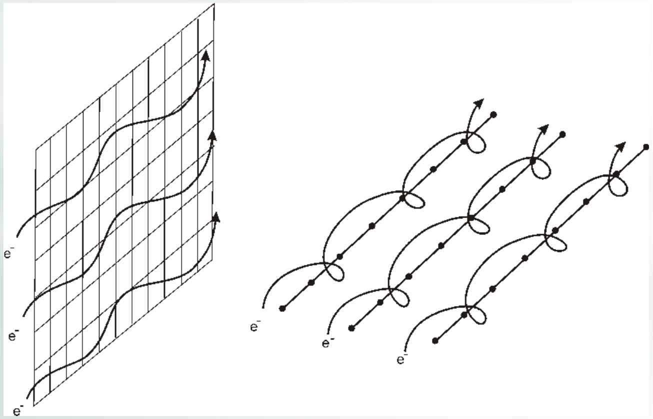
CHANNELING RADIATION

Channeling radiation: charged particles passing through the crystal along the direction of high symmetry (along the main crystallographic axes or planes).

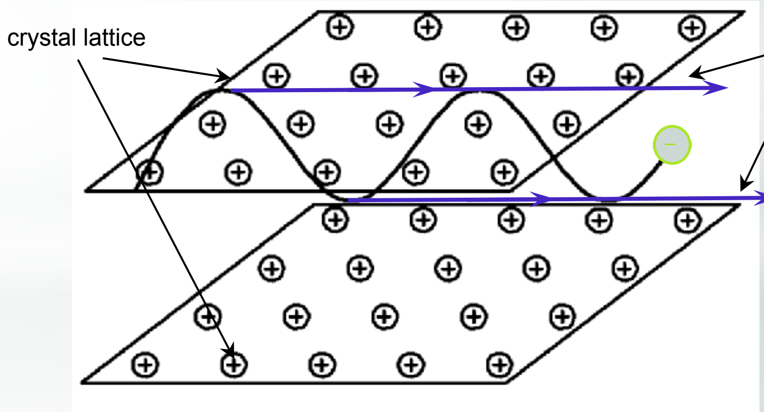
As known, the radiation is forward directed into a narrow cone with the angle of emission $\Theta \sim \gamma^{-1}$.

Three types of channeling are known:

- planar (charged particle is in averaged potentials of crystal planes),
- axial (particle moves along the crystal axe),
- stochastic channeling.



Planar and axial channeling



Electron motion between two crystallographic planes

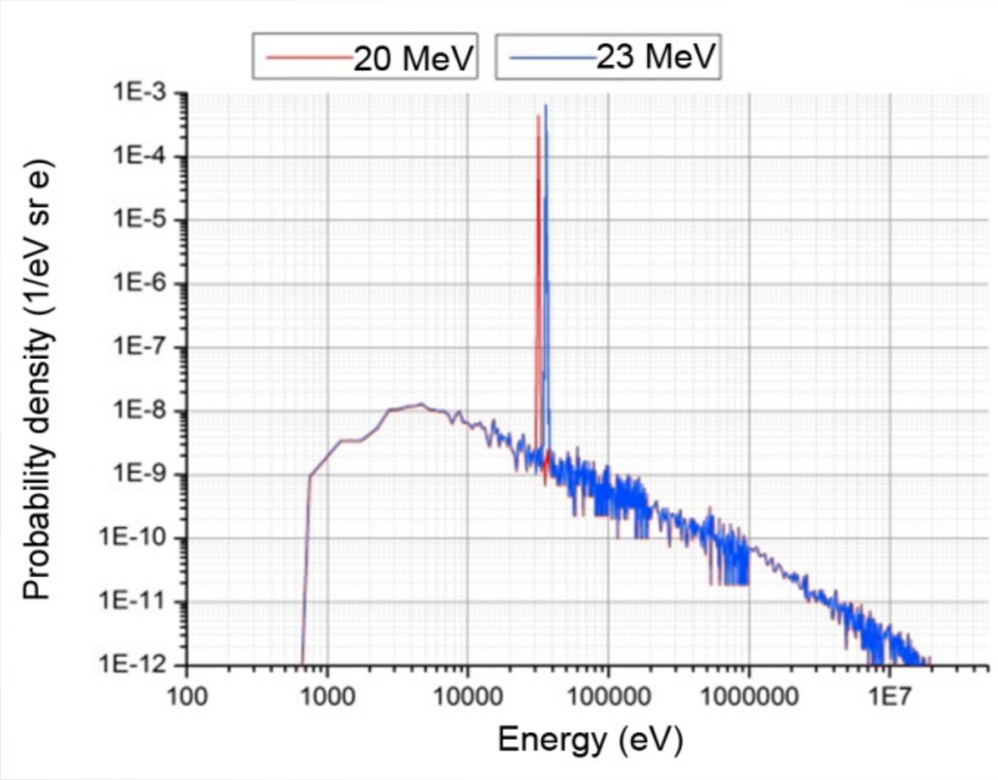
CAHNNELING RADIATION X-RAY SPECTRUM

Axial channeling radiation in 50 μm diamond has a maximums:

- 31.69 ± 2.18 keV for 20 MeV
- 36.33 ± 7.73 keV for 23 MeV.

Quantum efficiency for such crystal and beam energy is 1/2000 photon/electron. Thus, about $5 \cdot 10^{13}$ photons of 30 keV energy can be produced using 1 mA CW electron beam.

Important: to get that values we need an electron beam of very low energy spread ($\Delta E/E \sim 1\%$) as well as of limited envelope angle lower than the channeling critical angle (~1 mrad). The high precisions goniometer is also required for a fine crystal plane orientation.



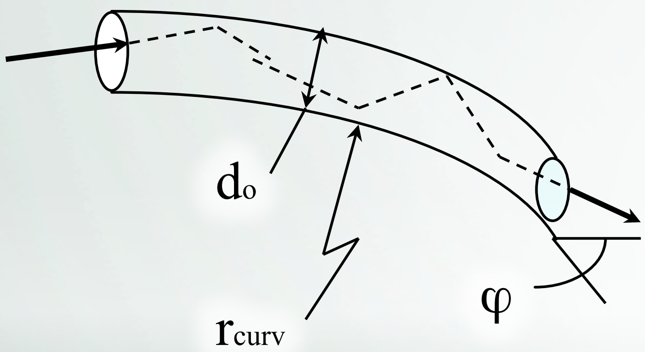
Channeling photon density distribution for 20 and 23 MeV electrons and diamond crystal

POLICAPILLARY OPTICS AS X-RAY MONOCHROMATOR

High-energetic X-ray tail of the spectrum can be eliminated by the monochromator. The best choice for this elements of the facility is polycapillary optics that provide high trasmission effciency with low radiation divergence angles (~ 1 mrad).

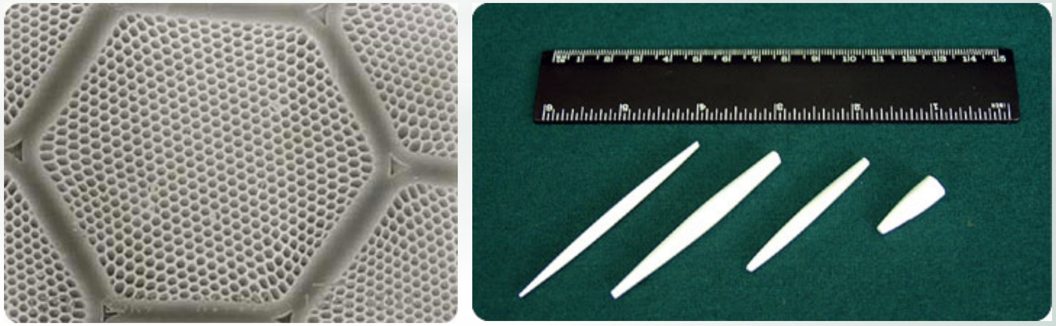
The efficiency of 30 keV photons transport is about 30-40 % with polycapyllary lens length 10 cm and capillary hollow 1-10 μm.

Important: capillary lens fits for irradiating large area (we need 5x5 to 40x40 cm^2).

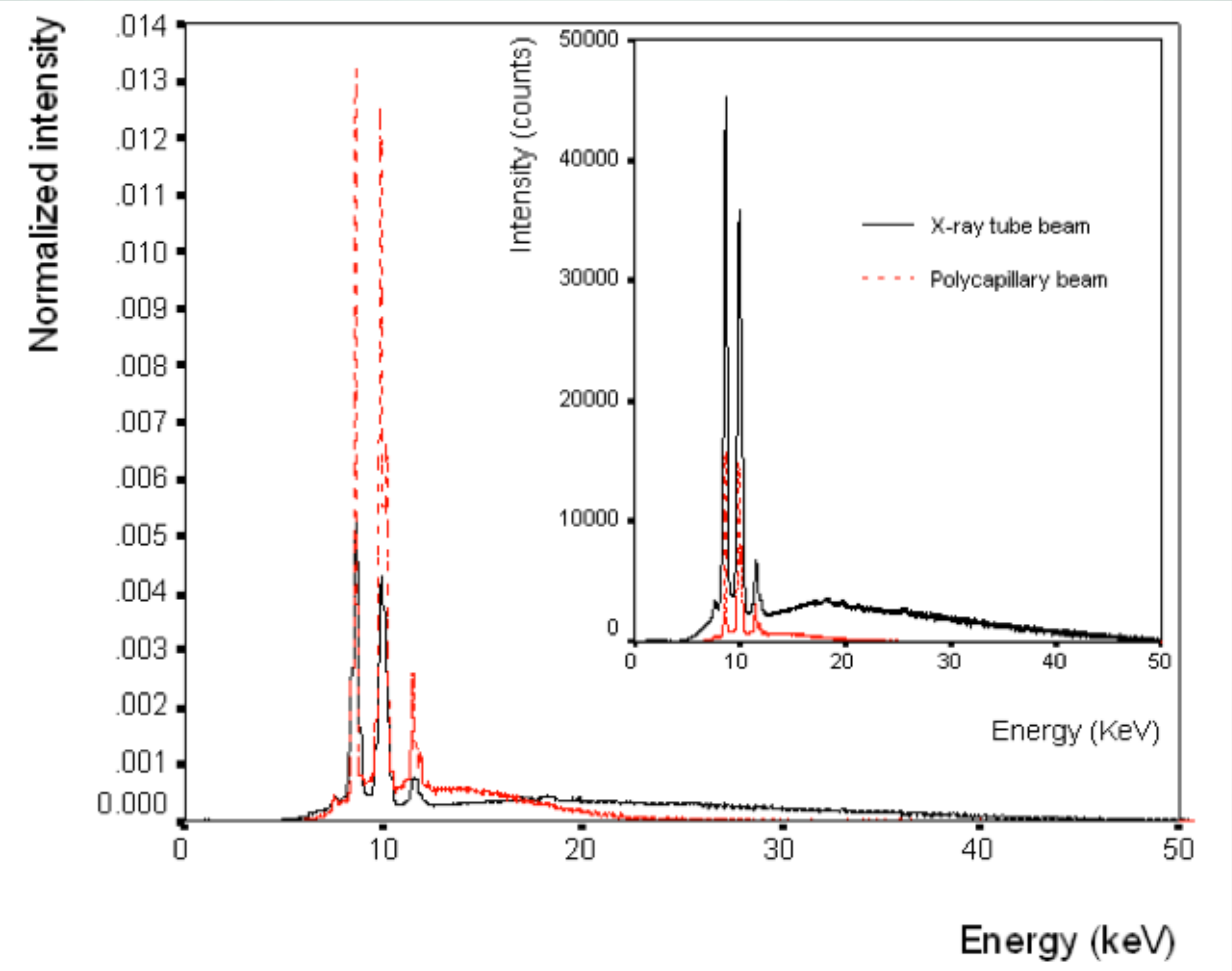


$$\theta_i \le \theta_c, \quad \frac{r_{curv}\theta_c^2}{2d_0} \ge 1$$

X-ray optics type	X-ray efficiency, %	
	17 keV	33 keV
Mosaic crystal	58	4.2
Log spiral reflector	35	0.04
Grazing incidence reflector	10	~0
Multilayer mirror	57	10
Polycapillary optics	60	40

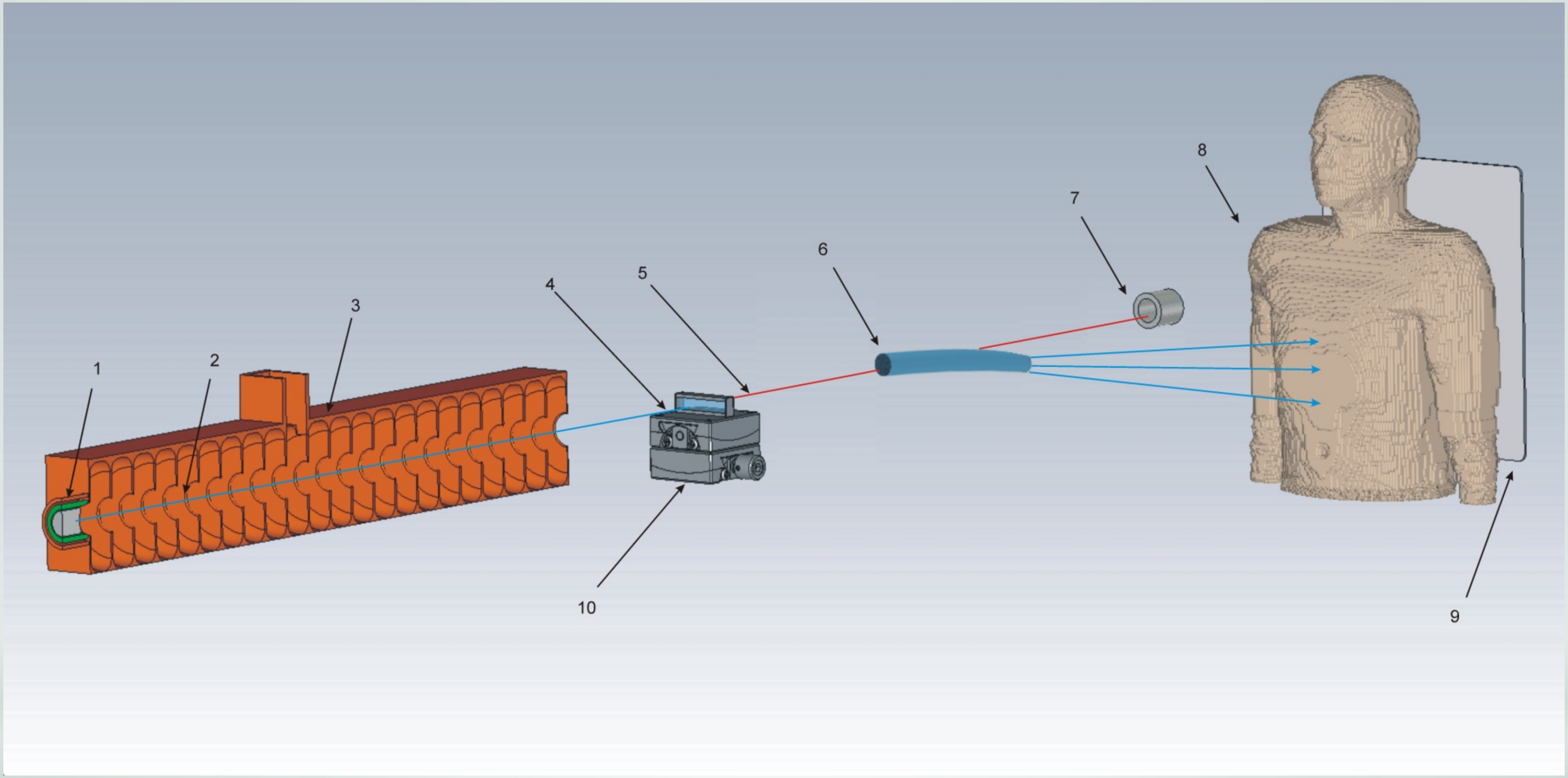


X-ray polycapillary optics end (left) and different geometries of the X-ray lenses (right)



Hard tail of radiation is cut off with polycapillary optics

FACILITY PRINCIPAL SCHEME



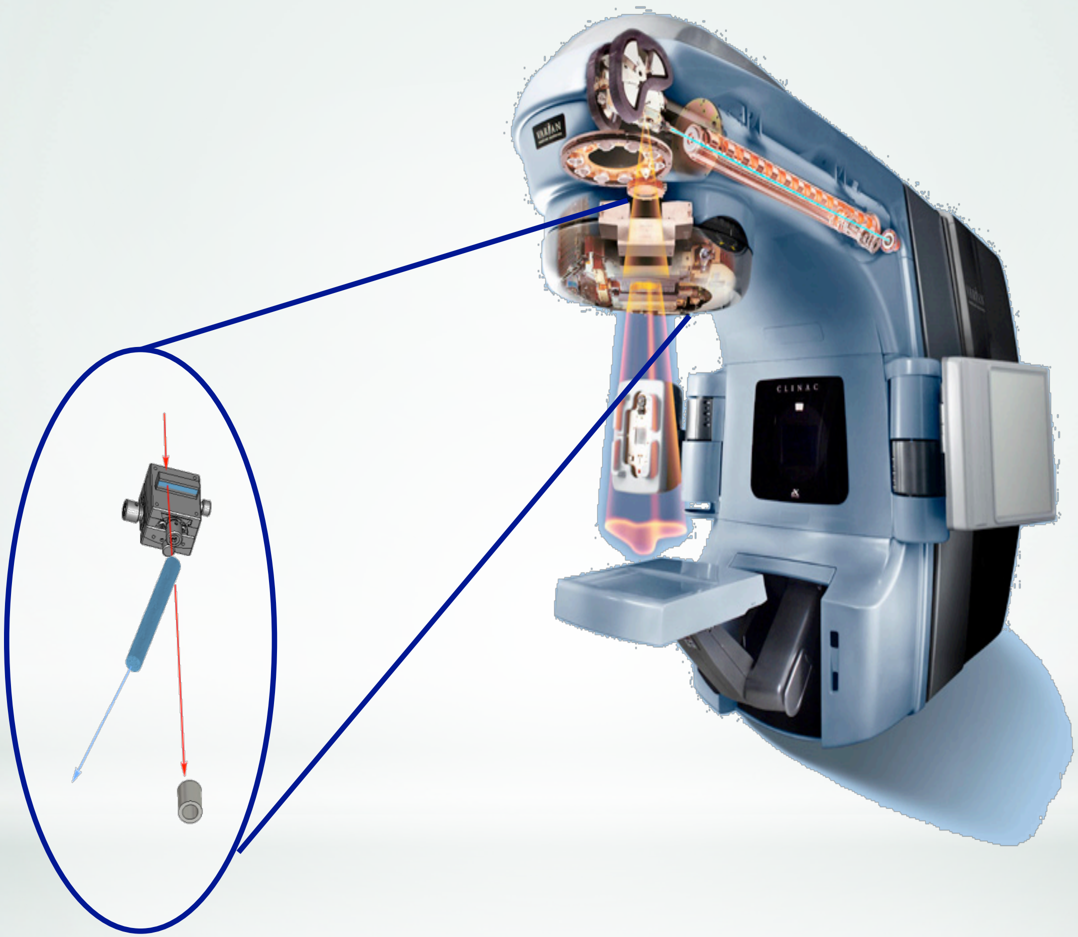
Principal scheme of monocrystal and polycapillary optics based X-ray source:

1 – electron gun, 2 – electron beam axis, 3 – accelerating structure,

4 – crystal, 5 – X-ray radiation, 6 – polycapillary lens,

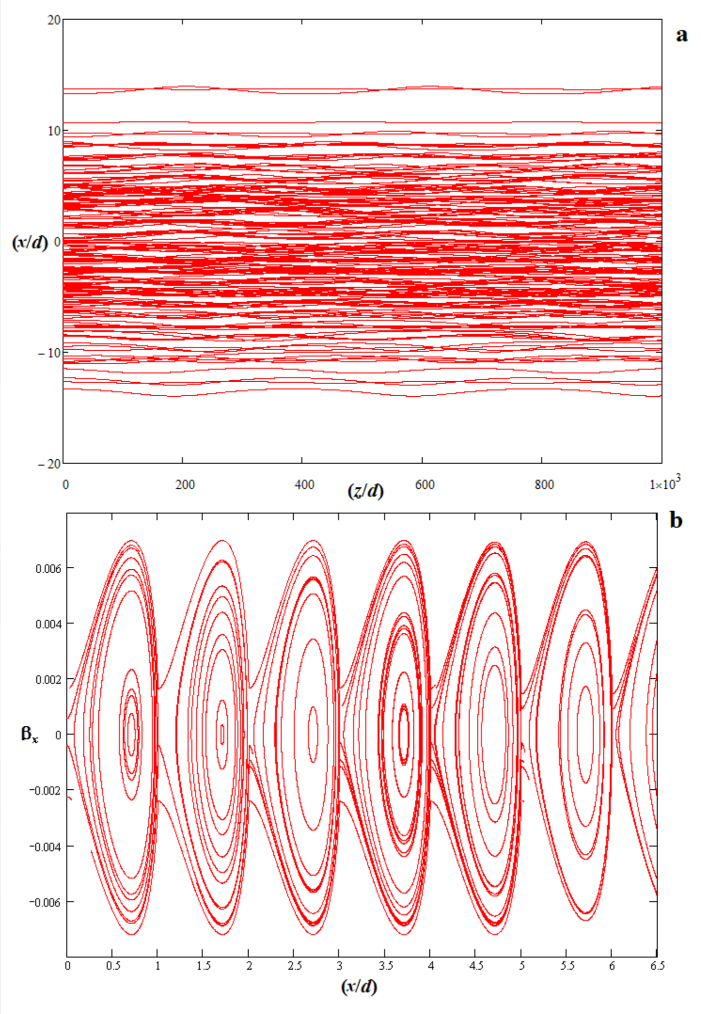
7 – bremsstrahlung X-ray radiation dump (both electrons and bremsstrahlung photons),
8 – patient body, 9 – X-ray detector, 10 – goniometer

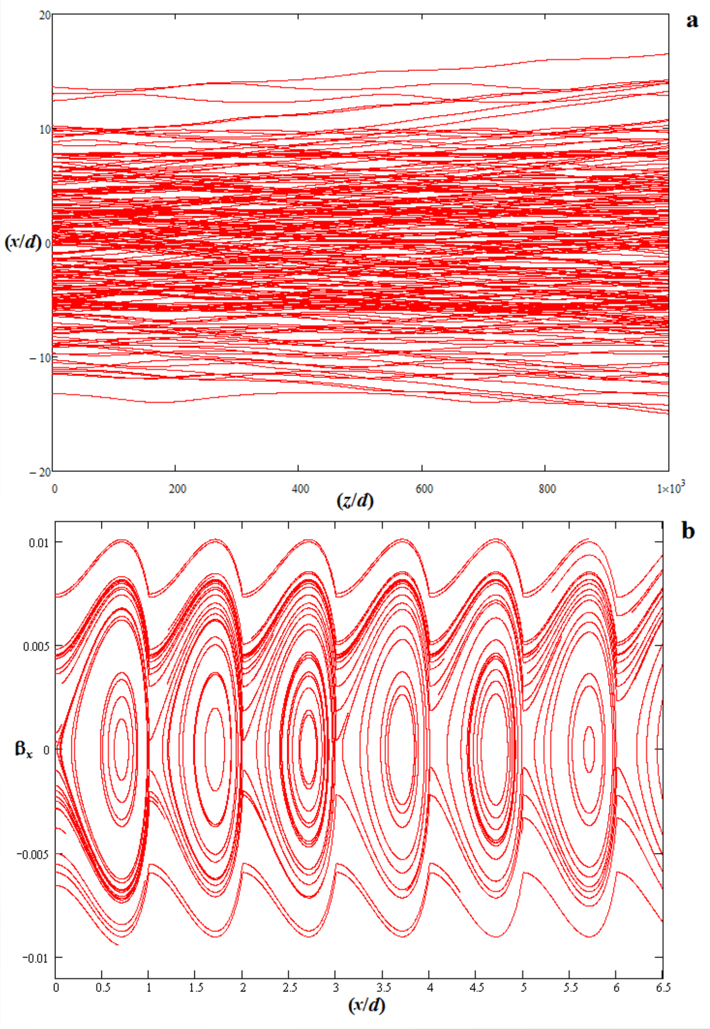
WAY OF REALIZATION



One of the possible ways of CR X-ray source realization for radiography or other medical applications based on serial linac for electron therapy (Varian, Siemens).

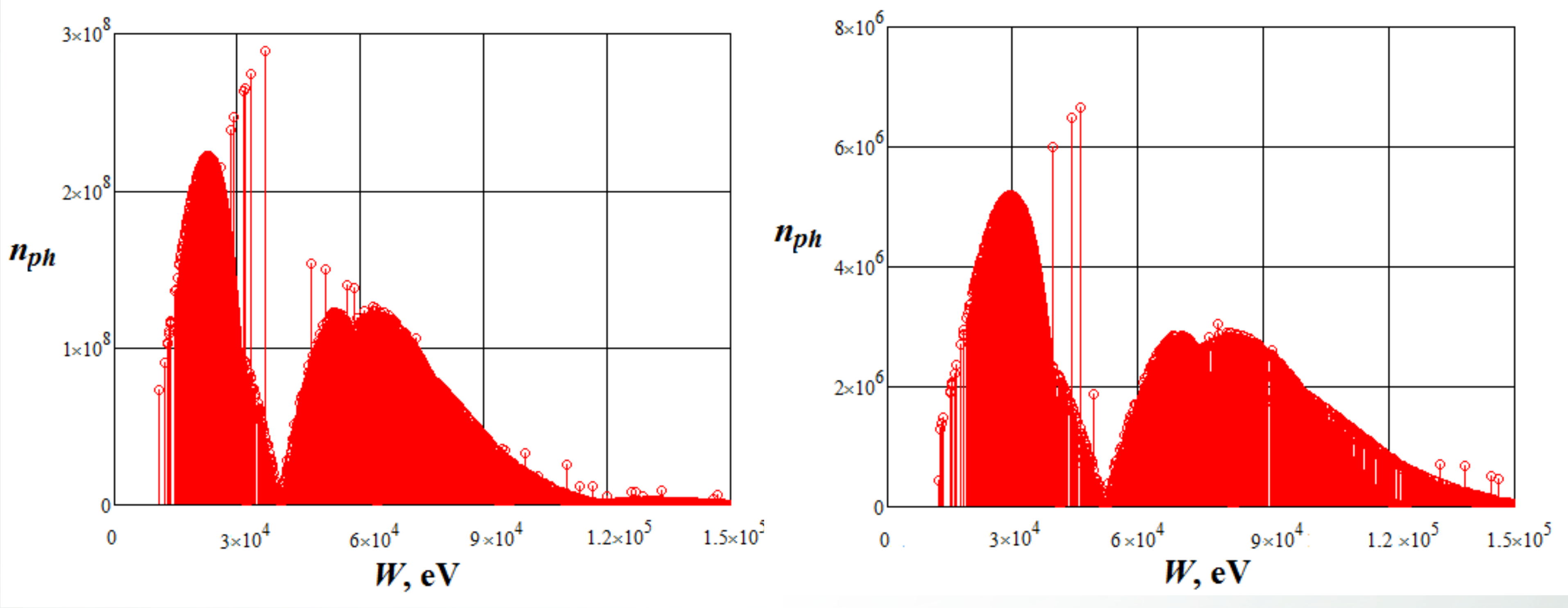
Channeling simulations performed in DINUS laboratory (MEPhI)



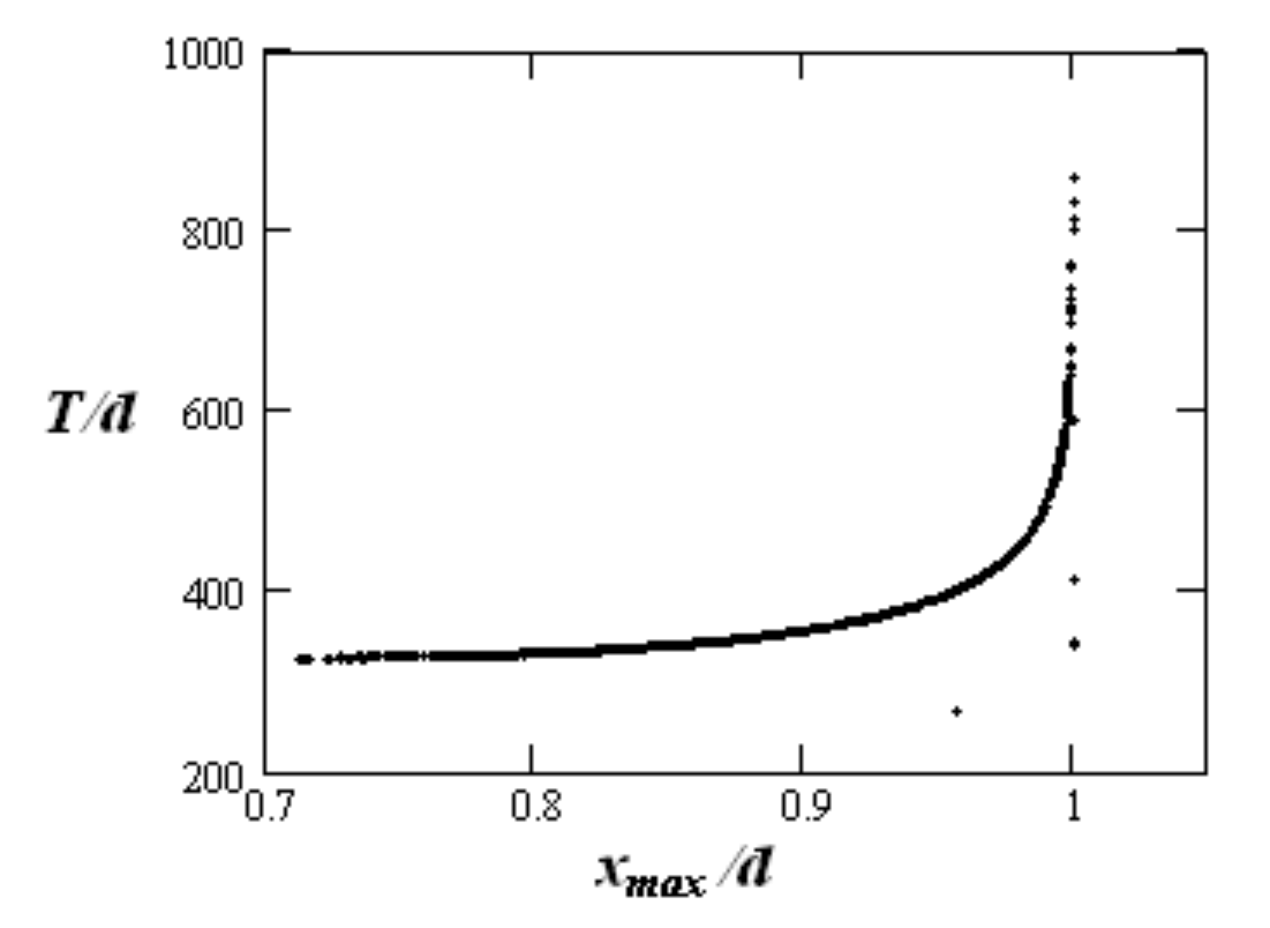


Trajectories of channeled electrons in (z, x) plane (a) and phase trajectories in (βr, r) phase plane (b) are shown

Channeling of electrons in case of large value of injection angle θ, dechanneled particles can be seen

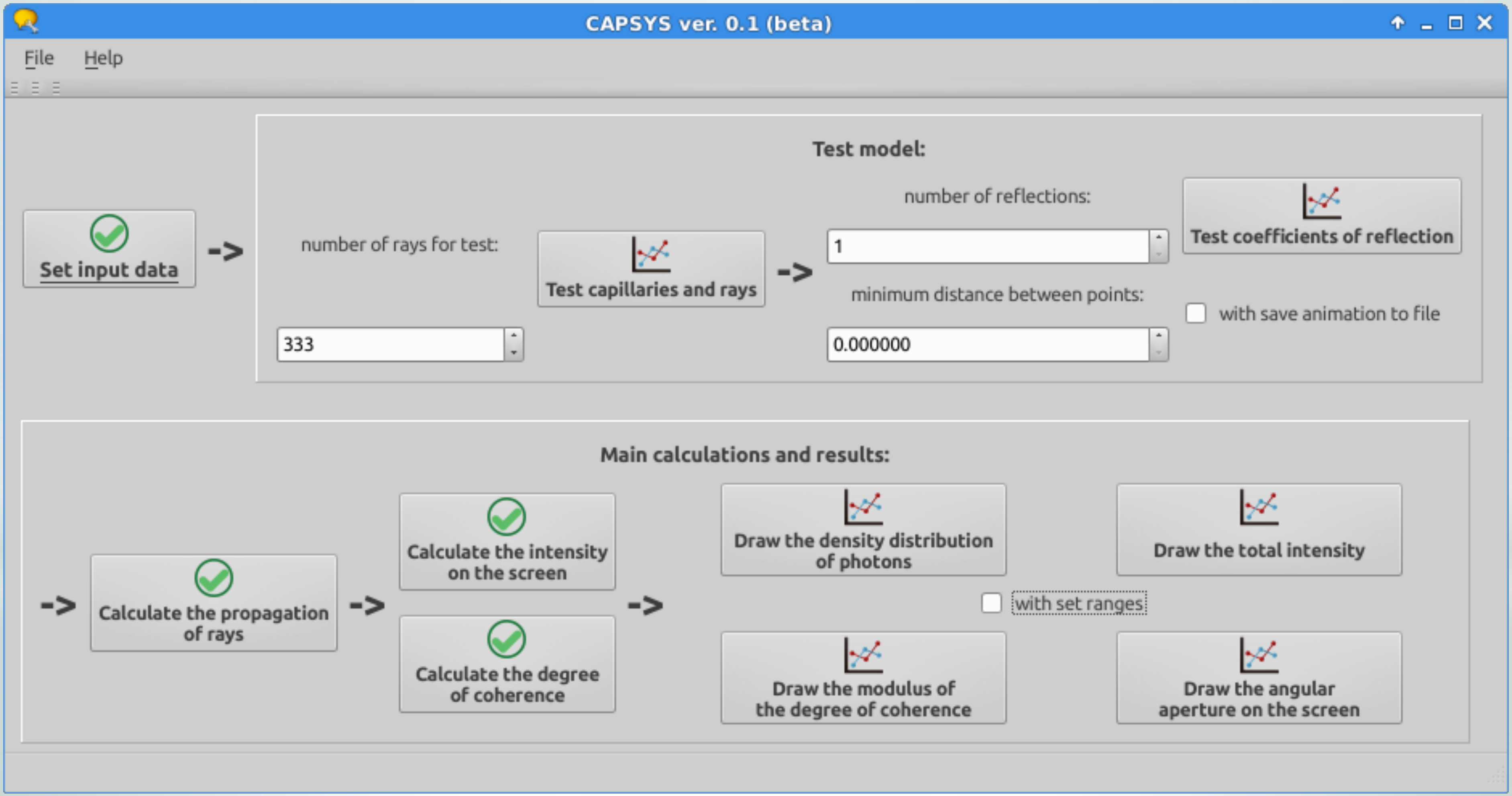


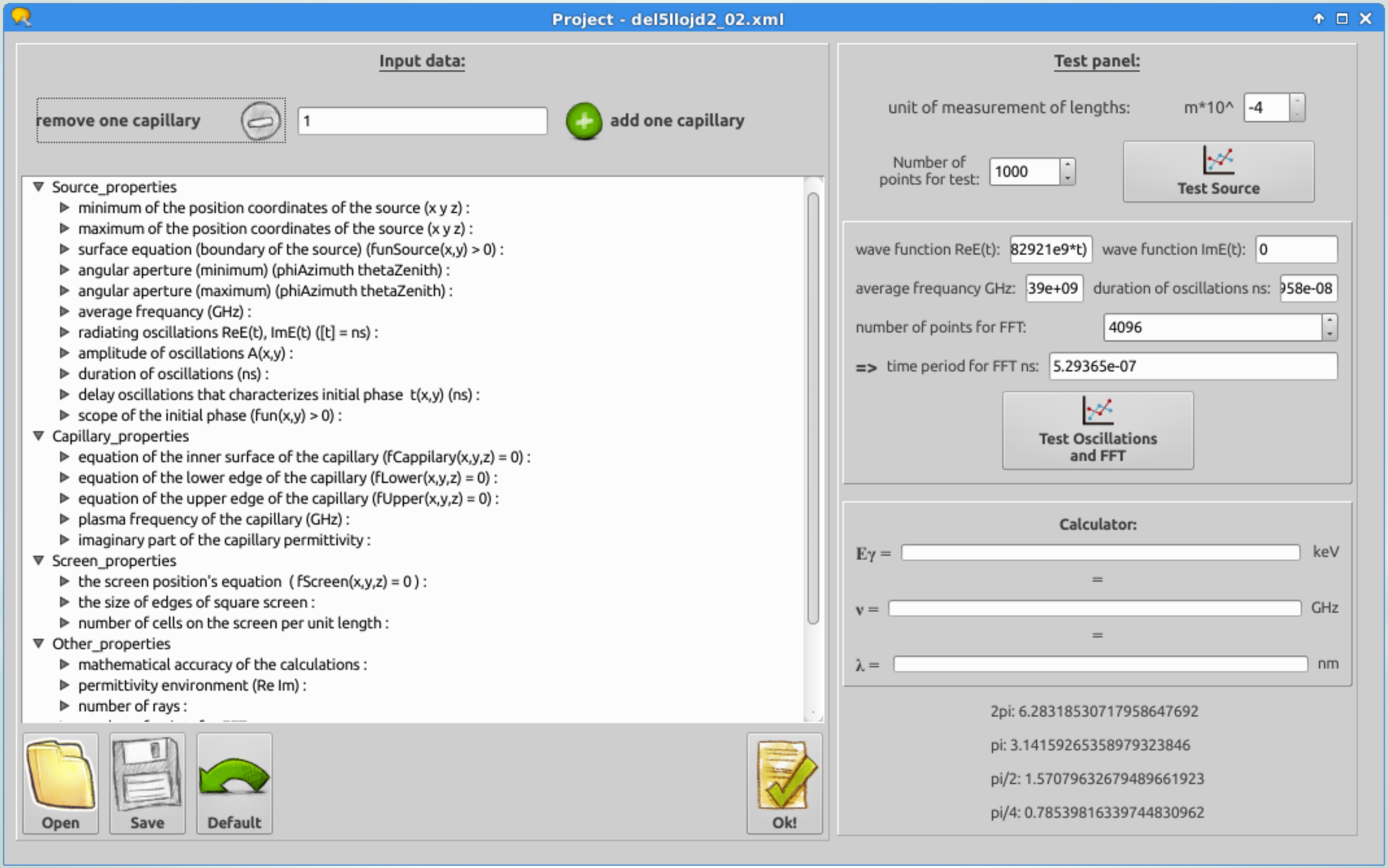
Typical energy distribution of radiated photons, electron's energy 21 MeV (left) and 25 MeV (right)



Dependence of electrons oscillation period (T/d) on oscillation amplitude (x_{max}/d)

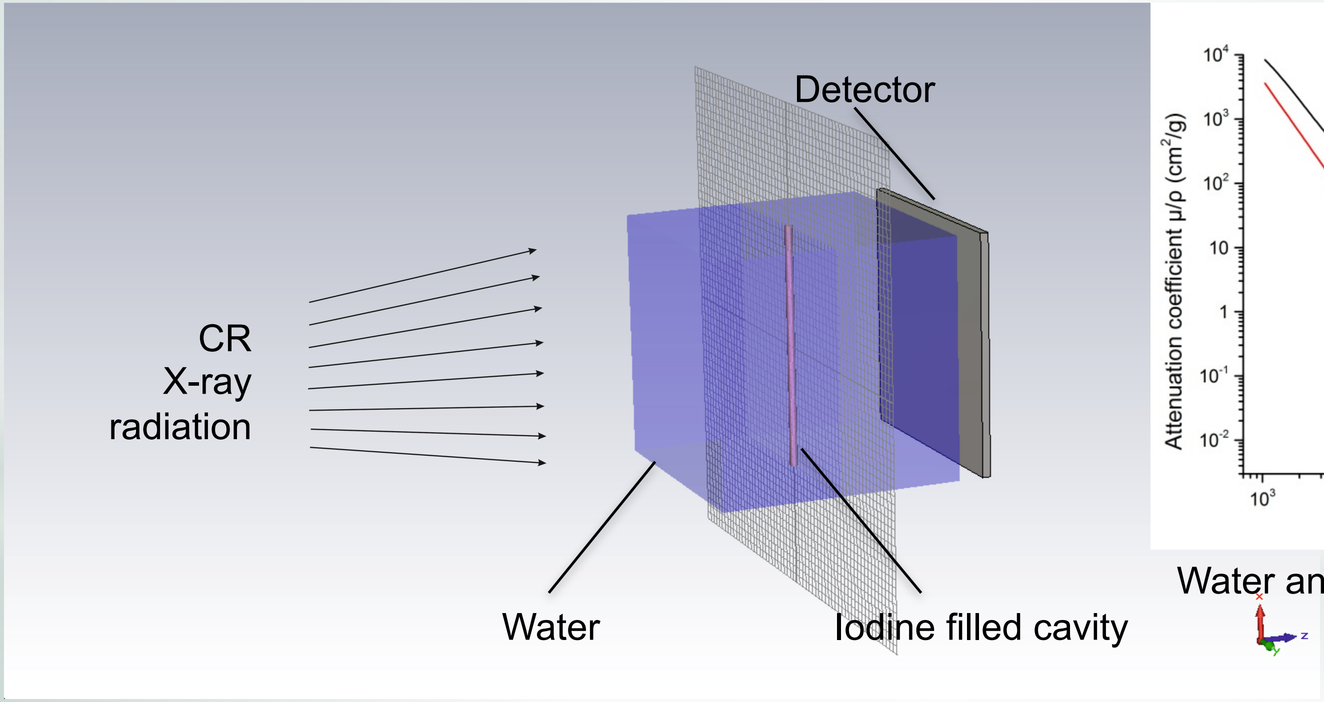
Program for calculating of photons captured by polycapillary lense (up to 1 million of channels!)



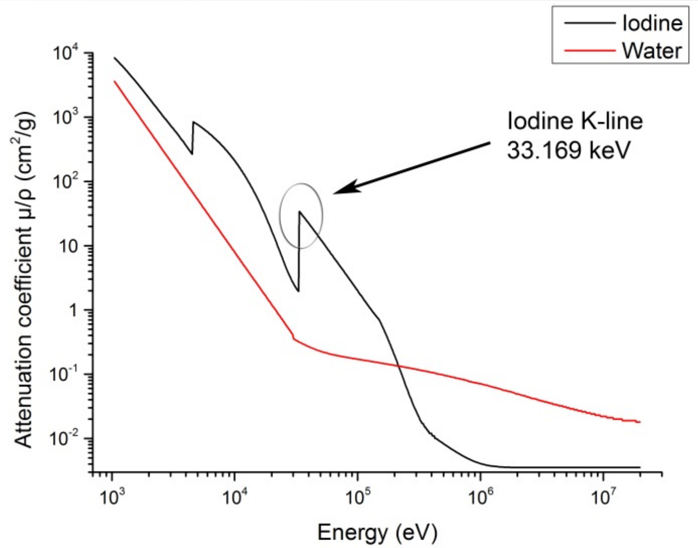

Project - del5llojd2_02.xml
Input data:
remove one capillary
1
add one capillary
Source_properties
minimum of the position coordinates of the source (x y z) :
maximum of the position coordinates of the source (x y z) :
surface equation (boundary of the source) (funSource(x,y) > 0) :
angular aperture (minimum) (phiAzimuth thetaZenith) :
angular aperture (maximum) (phiAzimuth thetaZenith) :
average frequancy (GHz) :
radiating oscillations ReE(t), ImE(t) ([t] = ns) :
amplitude of oscillations A(x,y) :
duration of oscillations (ns) :
delay oscillations that characterizes initial phase t(x,y) (ns) :
scope of the initial phase (fun(x,y) > 0) :
Capillary_properties
equation of the inner surface of the capillary (fCappilary(x,y,z) = 0) :
equation of the lower edge of the capillary (fLower(x,y,z) = 0) :
equation of the upper edge of the capillary (fUpper(x,y,z) = 0) :
plasma frequency of the capillary (GHz) :
imaginary part of the capillary permittivity :
Screen_properties
the screen position's equation (fScreen(x,y,z) = 0) :
the size of edges of square screen :
number of cells on the screen per unit length :
Other_properties
mathematical accuracy of the calculations :
permittivity environment (Re Im) :
number of rays :
Open
Save
Default
Ok!
Test panel:
unit of measurement of lengths:
m*10^
-4
Number of points for test:
1000
Test Source
wave function ReE(t):
82921e9*t)
wave function ImE(t):
0
average frequancy GHz:
39e+09
duration of oscillations ns:
958e-08
number of points for FFT:
4096
=> time period for FFT ns:
5.29365e-07
Test Oscillations and FFT
Calculator:
Eγ =
keV
=
ν =
GHz
=
λ =
nm
2pi: 6.28318530717958647692
pi: 3.14159265358979323846
pi/2: 1.57079632679489661923
pi/4: 0.78539816339744830962

ABSORBED DOSE CALCULATION MODEL

For estimation of the absorbed doses and image contrast the X-ray radiation attenuation in the tissue-equivalent phantom was investigated via the Beer-Lambert law. The phantom represents the water cube with the 30 cm edge and a cylindrical cavity with 1 mm diameter containing the 10% iodine contrast agent.



Absorbed doses investigation scheme



Water and iodine attenuation coefficients

ABSORBED DOSE CALCULATION

The photons number was calculated via the probability density curves using 10^{12} electrons. Polycapillary optics employment in case of 20 MeV channeling radiation source allows reducing dose acquired by the phantom 54 times vs. the generation system without optics and gives $4.3\cdot10^{-5}$ Sv with $2.28\cdot10^{11}$ photons. Analogous system with 23 MeV electron source gives 30 times energy reduction and gives $8.1\cdot10^{-5}$ Sv with $3.78\cdot10^{11}$ photons. The conventional 100 keV X-ray tube with W-Re anode provides $5.6\cdot10^{-6}$ Sv with $2.2\cdot10^{10}$ photons.

Source	Photons number	Absorbed dose, μSv
CR 20 MeV	$2.2\cdot10^{11}$	43
CR 23 MeV	$3.78\cdot10^{11}$	81
X-ray tube 100 keV	$2.2\cdot10^{10}$	5.6

$$I_{pas} = \sum_{W_i} K\cdot I(W_i)\cdot W_i \cdot e^{-\mu/\rho(W_i)\cdot\rho\cdot l}$$

$$I_{abs} = \sum_{W_i} K\cdot I(W_i)\cdot W_i \cdot \left(1-e^{-\mu/\rho(W_i)\cdot\rho\cdot l}\right)$$

$$D = \frac{\sum_{W_i} K\cdot I(W_i)\cdot W_i \cdot \left(1-e^{-\mu/\rho(W_i)\cdot\rho\cdot l}\right)}{M}$$

Here I_{pas} – passed radiation intensity, I_{abs} - absorbed radiation intensity, D – absorbed dose, K – number of electron from the source, W_i – photon energy, $I(W_i)$ – possibility density of the electron emission, $\mu/\rho(W_i)$ – medium absorption coefficient, ρ – medium density, l – radiation path in the irradiated object, M – irradiated object mass

IMAGE CONTRAST CALCULATION

The image contrast was investigated as a cylindrical cavity visibility against the background of the radiation passed through the water cube. So the contrast will be the value of the energy passed through the water vs. the energy passed through the water and iodine ratio.

The 20 MeV channeling source provides lower contrast of the iodine-filled cavity (**0.8** of the X-ray tube image contrast) because the maximum channeling intensity peak of the radiation lies in the area of small iodine attenuation coefficients.

The contrast of iodine-filled cavity measured in these three cases shows that the 23 MeV channeling radiation source + polycapillary optics gives **3 times** higher of contrast image of the cavity than the conventional X-ray tube + convetional filters.

Acknowledgements

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- Ivan Ergunov (MEPhI)
- Sergey Polozov (MEPhI, laboratory DINUS)

Thank you!

Electron dynamics simulation in crystal in effective potential approach

$$U(x) = U_0 \sum_{n=0}^{N} a_n \left(\frac{x}{d}\right)^n \qquad |x| < d$$

$$\Omega_n = \sqrt{2}\Omega_0, \quad \Omega_0 = \frac{c}{d}\sqrt{\frac{2eU_0}{\varepsilon}}$$

Power of radiation losses of electron due to channeling radiation is defined by the equation:

$$P = \frac{2e^4 < E^2 > \gamma^2}{3m^2 c}$$

In the general the spectral and angle distribution of the irradiated energy can be defined as the sum

$$\frac{d^2\varepsilon}{d\omega d\theta} = \frac{e^2}{\pi^2 c}\sum_{k=1}^{\infty}\frac{|\boldsymbol{a}_k(\omega,\theta,\varphi)|^2}{\Omega^2}\frac{\sin^2(\pi K \sigma_k)}{\sigma_k^2} \qquad \boldsymbol{a}_k = \frac{\Omega}{2\pi}\int_0^{2\pi/\Omega}\boldsymbol{a}(t)e^{ik\Omega t}\,dt$$

$$\boldsymbol{a}(t) = \left[\boldsymbol{n}\left[\boldsymbol{n} - \beta\right]\dot{\beta}\right](1 - \boldsymbol{n}\beta)^{-2}\exp\left[-\frac{i\omega}{c}\left(n_x x + n_y y + n_z \delta z\right)\right]$$

$$\sigma_k(\omega,\theta) = \Omega^{-1}\left[\omega(1 - n_z\beta_z) - k\Omega\right] \qquad n_x = \sin\theta\cos\varphi \qquad n_x = \cos\theta \qquad n_y = \sin\theta\sin\varphi$$