Rutherford backscattering spectrometry

	RBS	**Middle Energy Ion Scattering (MEIS)**
	H^+, He^+… 1 – 5 MeV, traditionally He^+ 2 MeV	H^+, He^+… 50 – 300 keV
Film (layer) thickness	10 – 5000 nm	1 – 500 nm
Depth resolution (for near-surface layer)	~ 10 nm	~ 0.5 nm

The information about the sample under investigation, provided by Rutherford Backscattering Spectrometry

Geometry

1. Layer (film) thickness;
2. Thickness heterogeneity;
3. Substrate coverage rate;
4. Interface (interdiffusion, dislocations).

Element composition

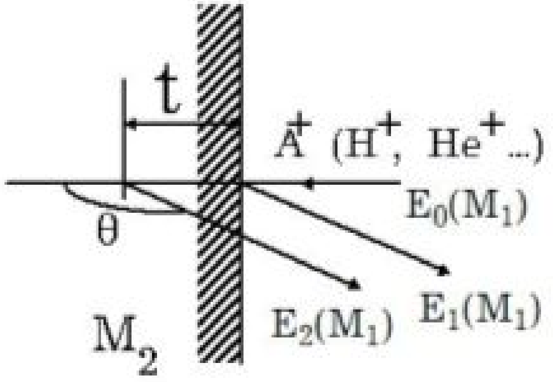
1. Multi-element film stoichiometry and its depth dependence.
2. Depth dependence of impurity atomic density.

Crystalline structure. Types and concentration of defects

1. Differential diagnostics of point and continuous defects;
2. Depth dependence of point defects concentration;
3. Block disorientation angle in textured films;
4. Impurity atoms position in crystalline lattice.

The basic moments of RBS-MEIS

1. Kinematical factor



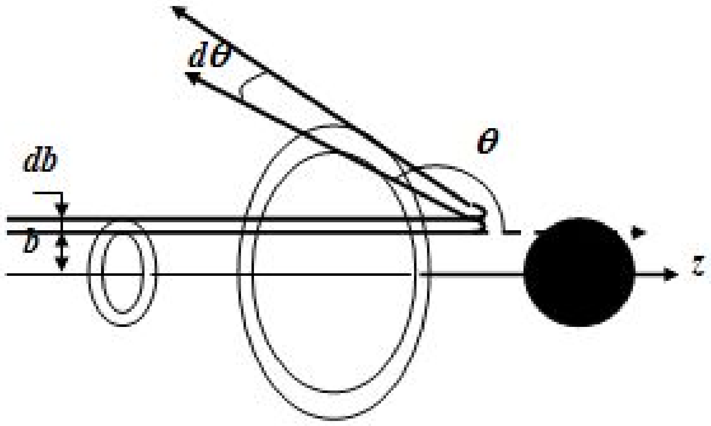
$$\mathbf{E_1 = \mathit{K} \cdot E_0}$$

$$K = \left\{ \frac{\left[1-(M_1/M_2)^2 \sin^2\theta\right]^{1/2} + (M_1/M_2)\cos\theta}{1+(M_1/M_2)} \right\}^2$$

$$\mathit{If}\ \theta = 180^\circ\ \mathit{then}\quad K = \left\{ \frac{1-M_1/M_2}{1+M_1/M_2} \right\}^2$$

If $M_2 = M_1$ *then* $K = 0$; *if* $M_2 >> M_1$ *then* $K \cong 1$

2. Scattering cross section



$$\sigma(\theta) = \left(\frac{Z_1 Z_2 e^2}{4E \cdot Sin^2(\theta/2)} \right)^2$$

The θ-angle scattering probability for ions moving through $\tau = n*t$ [at./cm^2] thickness layer is $Y = \sigma(\theta) \cdot \Omega \cdot \tau$, Ω being the detector spatial angle.

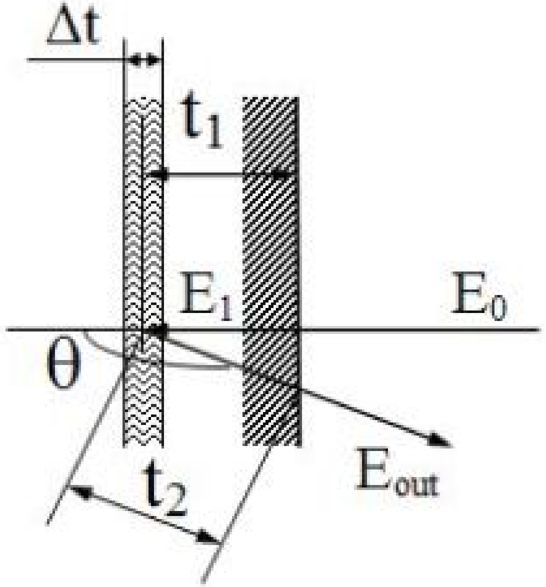
3. Stopping cross section ε [eV/(at./cm²)], stopping power S [eV/cm]

Scattered ion output energy after passing the layer having the thickness τ [at./cm^2]

$$E_2 = (E_0 - \bar{\varepsilon}_{in} \cdot \tau) \cdot K - \bar{\varepsilon}_{out} \cdot \frac{\tau}{|Cos\,\theta|}$$

If the atomic density n is known, then

$t = \tau/n$, $S = \varepsilon n$



$$E_1 = E_0 - S \cdot t_1$$

$$E_{out} = K \cdot E_1 - S \cdot t_2 = K \cdot (E_0 - S \cdot t_1) - S \cdot t_1 / \cos(\pi - \theta)$$

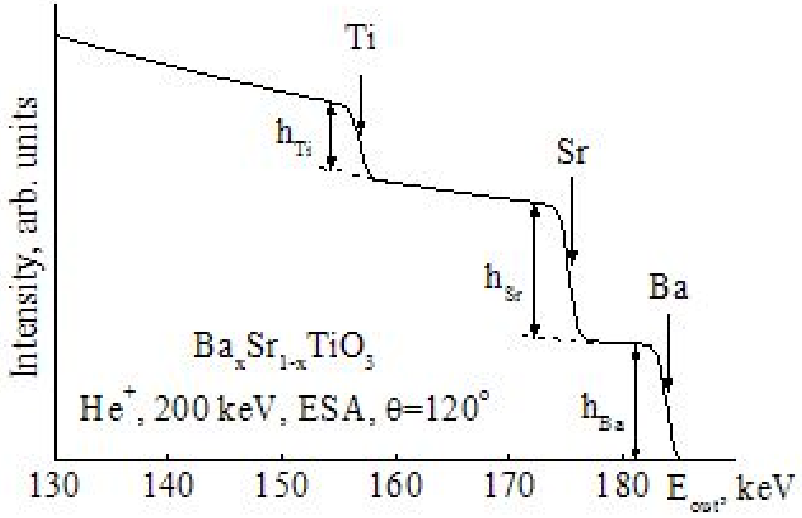
$$t_1 = \frac{K \cdot E_0 - E_{out}}{S \cdot \left(K + \frac{1}{\cos(\pi - \theta)} \right)}; \quad |\Delta t| = \frac{\delta E}{S \cdot \left(K + \frac{1}{\cos(\pi - \theta)} \right)}$$

$$I(E_{out}) = I_0 \cdot \left(\frac{Z_1 \cdot Z_2 \cdot e^2}{4 \cdot E_1(E_{out}) \cdot \sin^2 \frac{\theta}{2}} \right)^2 \frac{N \cdot \delta E \cdot \Delta\Omega}{S \cdot \left(K + \frac{1}{\cos(\pi - \theta)} \right)}$$

Taking into account $S = \varepsilon \cdot N$

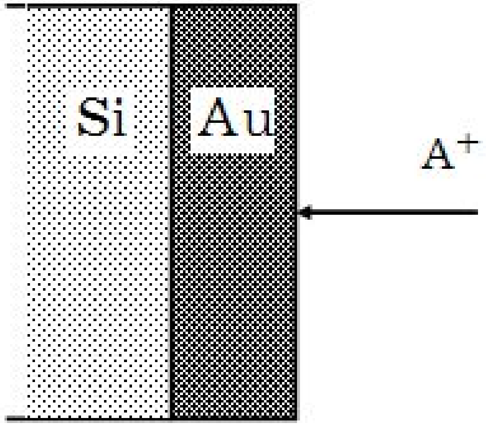
$$I(E_{out}) = I_0 \cdot \left(\frac{Z_1 \cdot Z_2 \cdot e^2}{4 \cdot E_1(E_{out}) \cdot \sin^2 \frac{\theta}{2}} \right)^2 \frac{\delta E \cdot \Delta\Omega}{\varepsilon \cdot \left(K + \frac{1}{\cos(\pi - \theta)} \right)}$$

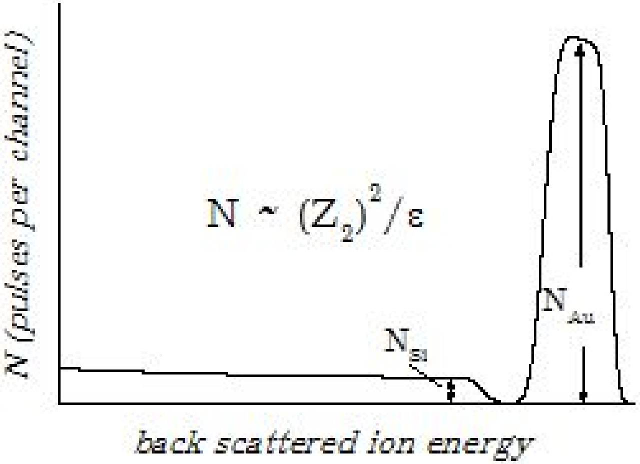
For ESA $\delta E = C \cdot E_{out}$



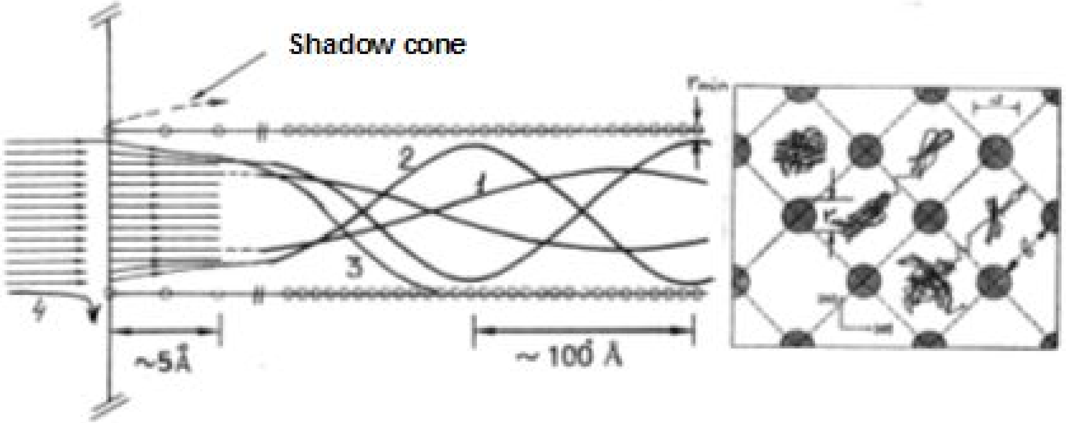
$$\frac{h_{Ba}}{h_{Sr}} = \frac{x \cdot Z_{Ba}^2}{(1-x) \cdot Z_{Sr}^2}, \text{ from which } x = \frac{\frac{h_{Ba}}{h_{Sr}} \cdot Z_{Sr}^2}{Z_{Ba}^2 + \frac{h_{Ba}}{h_{Sr}} \cdot Z_{Sr}^2}$$

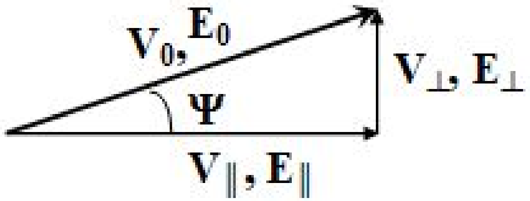
Inserting $Z_{Ba} = 56$ *and* $Z_{Sr} = 38$, *we find* $x \cong 0.3$.

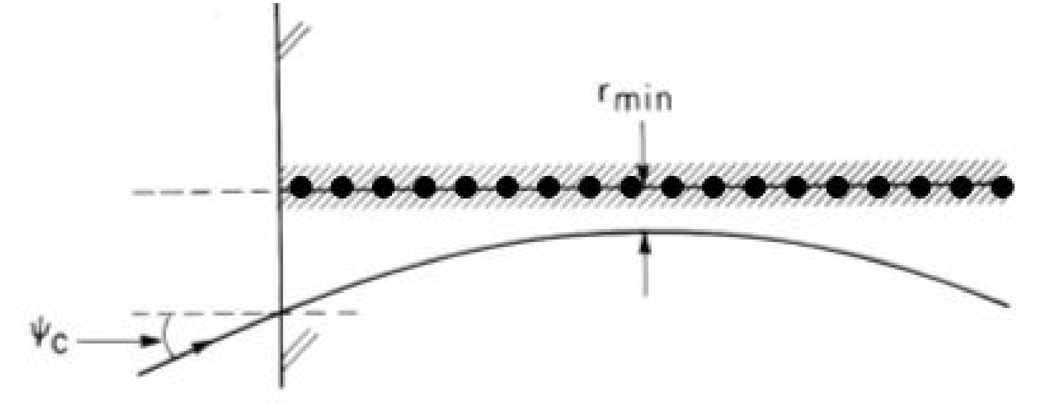




Fast ion channeling in single crystals







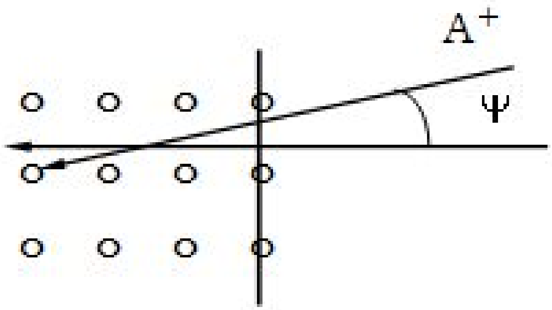
$E_\perp = E_0 \cdot \mathrm{Sin}^2\Psi \cong E_0 \cdot \Psi^2$

$E_\perp = U(r_{min})$;

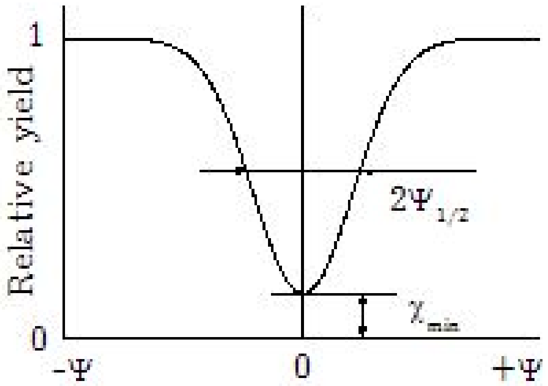
$r_{min} \sim 0.01$ nm;

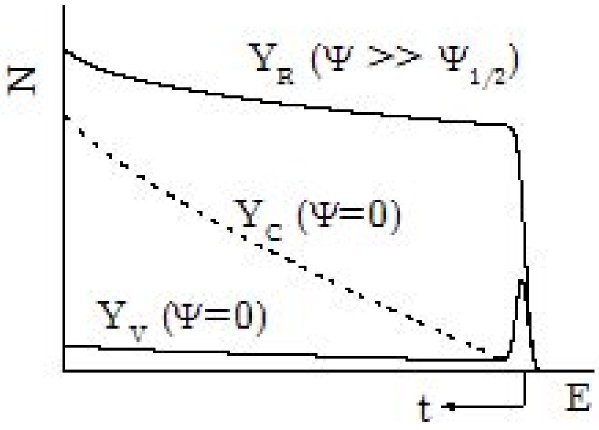
He^+ 1 MeV → Si [100]

$\Psi_C = 0.7^\circ$



$$\chi_{\min} = \frac{Y_C}{Y_R}$$





Y_R – backscattering yield for non-oriented ("random") regime.

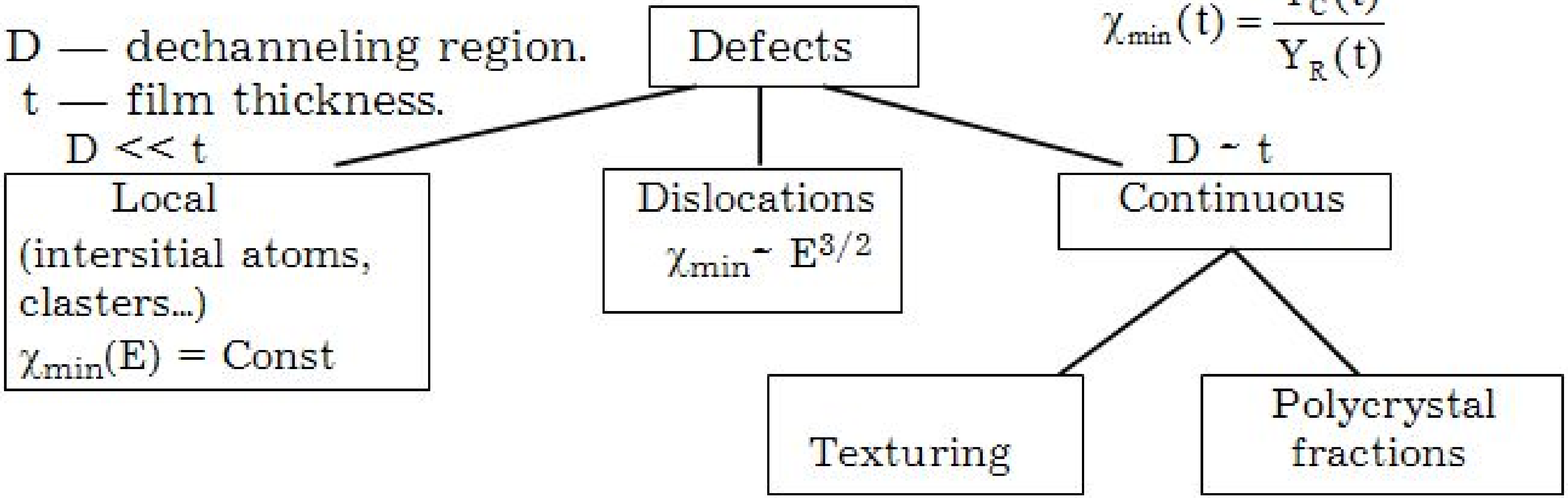
Y_V and Y_C – yield in aligned or channeling regime in the absence and presence of point defects, respectively.

Under the assumption that $n_D << n \rightarrow Y_C(t)/Y_R(t) \cong Y_V(t)/Y_R(t) + \sigma_D n_D \cdot t$, where

n_D — defect concentration, n — crystal atoms atomic density.

D — dechanneling region.
t — film thickness.

$$\chi_{min}(t) = \frac{Y_C(t)}{Y_R(t)}$$



Defects

D << t

Local
(intersitial atoms, clasters...)
$\chi_{min}(E)$ = Const

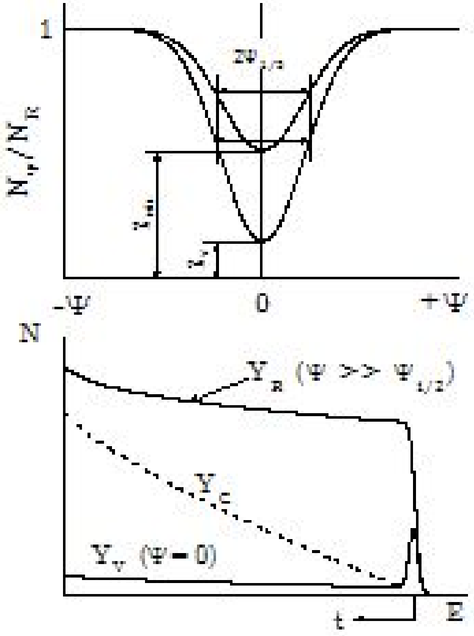
Dislocations
$\chi_{min} \sim E^{3/2}$

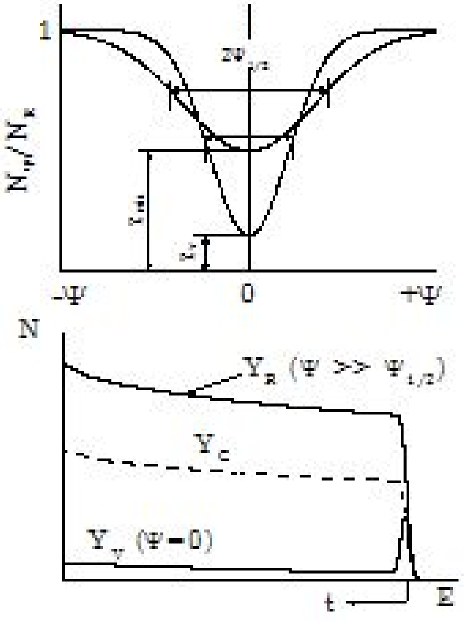
D ~ t

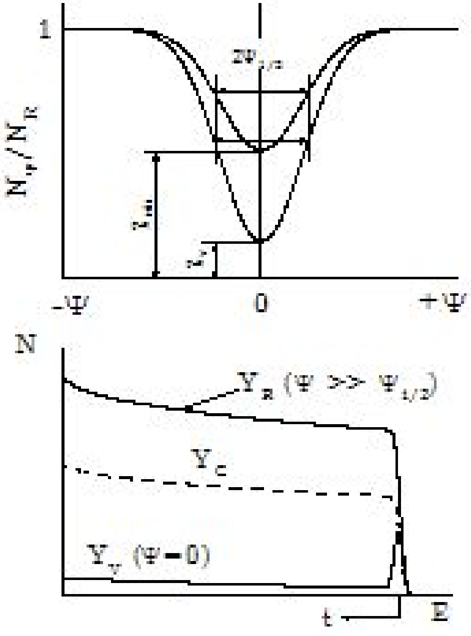
Continuous

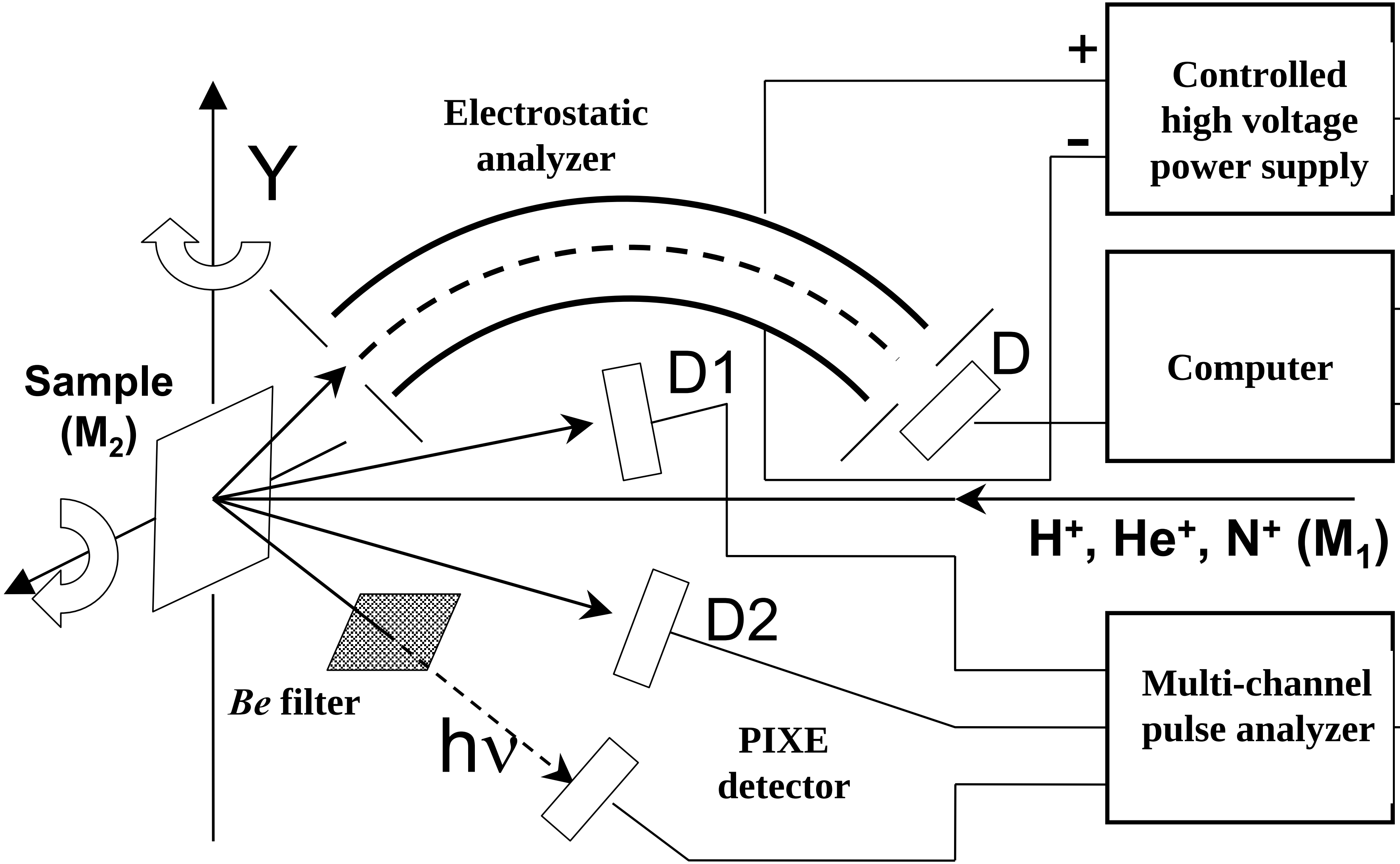
Texturing

Polycrystal fractions

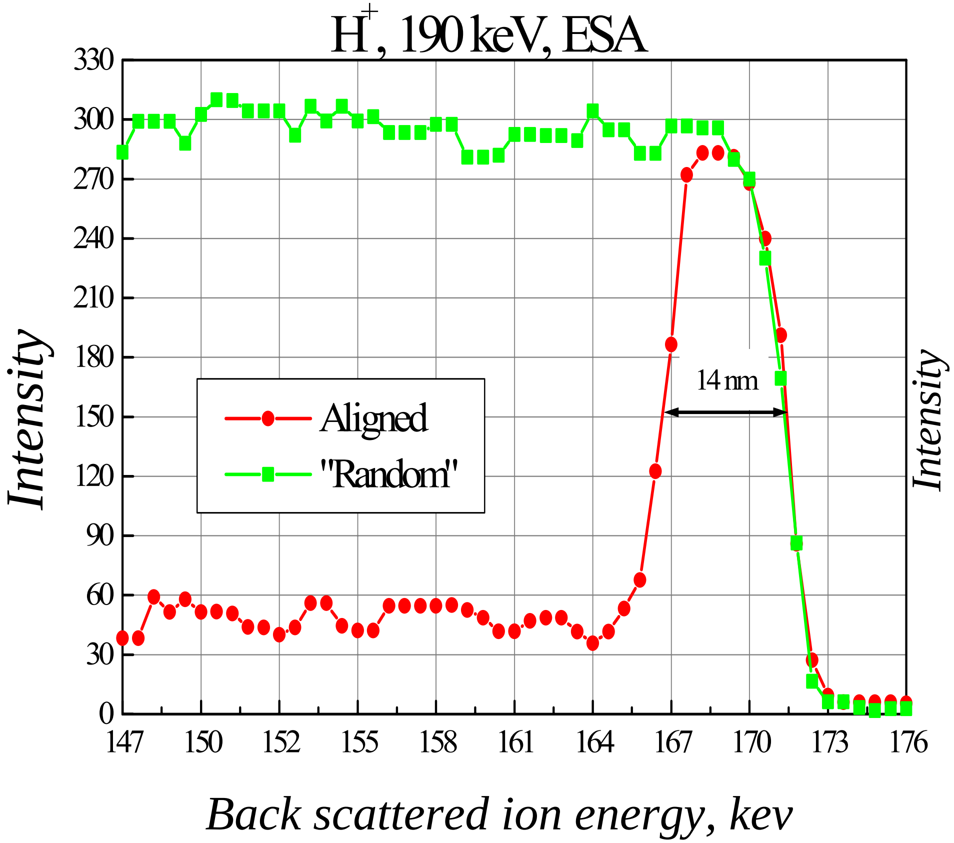






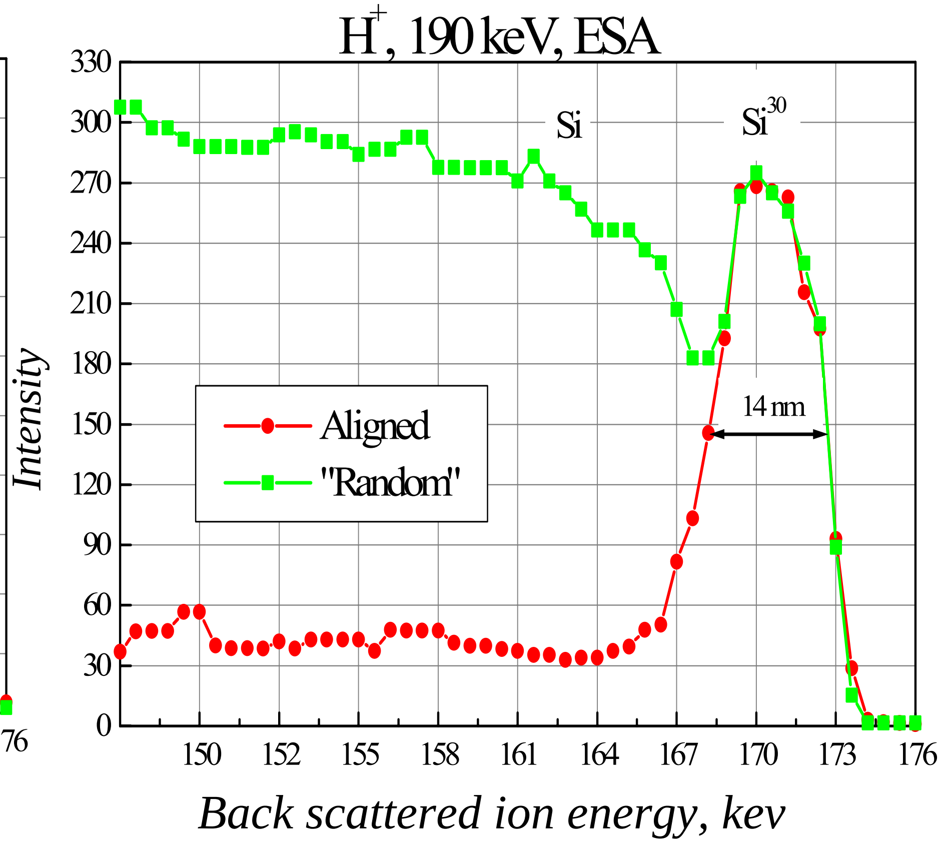


Electrostatic analyzer
Y
+
-
Controlled high voltage power supply
Computer
D
D1
D2
Sample (M$_2$)
H$^+$, He$^+$, N$^+$ (M$_1$)
Be filter
hν
PIXE detector
Multi-channel pulse analyzer



(Si_{pol}/Si_{mon}) sample spectra

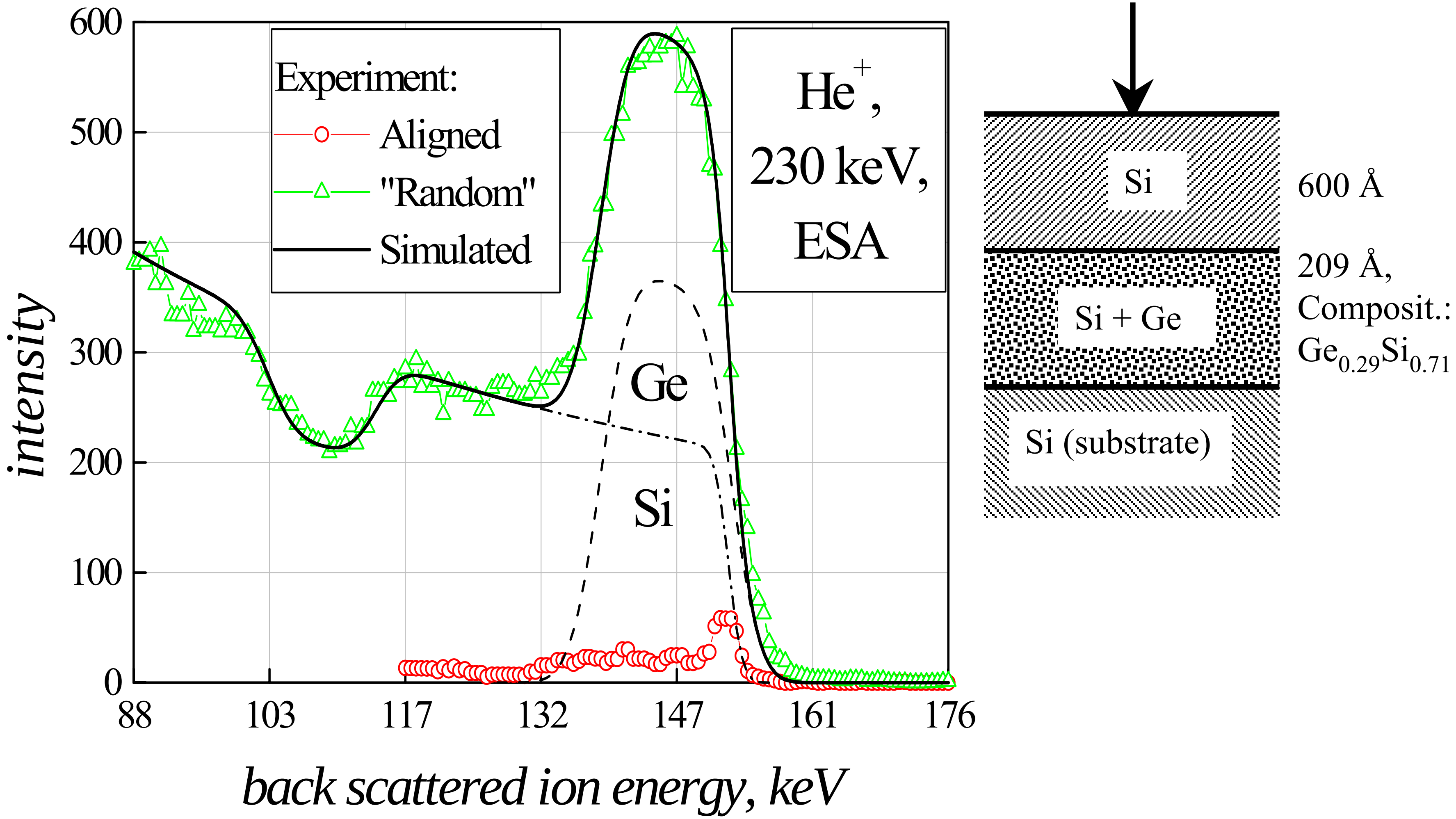
H^+, 190 keV, ESA

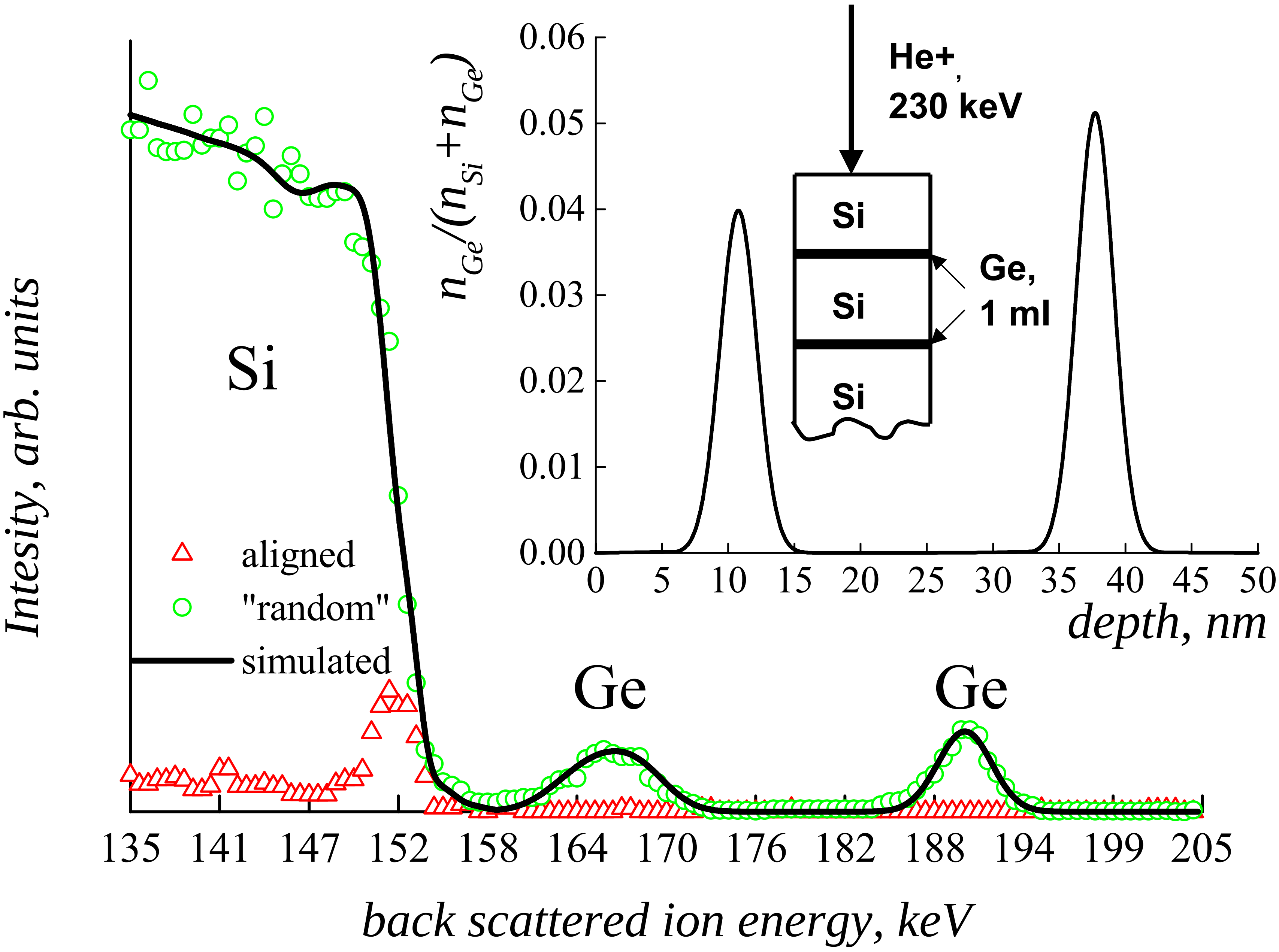


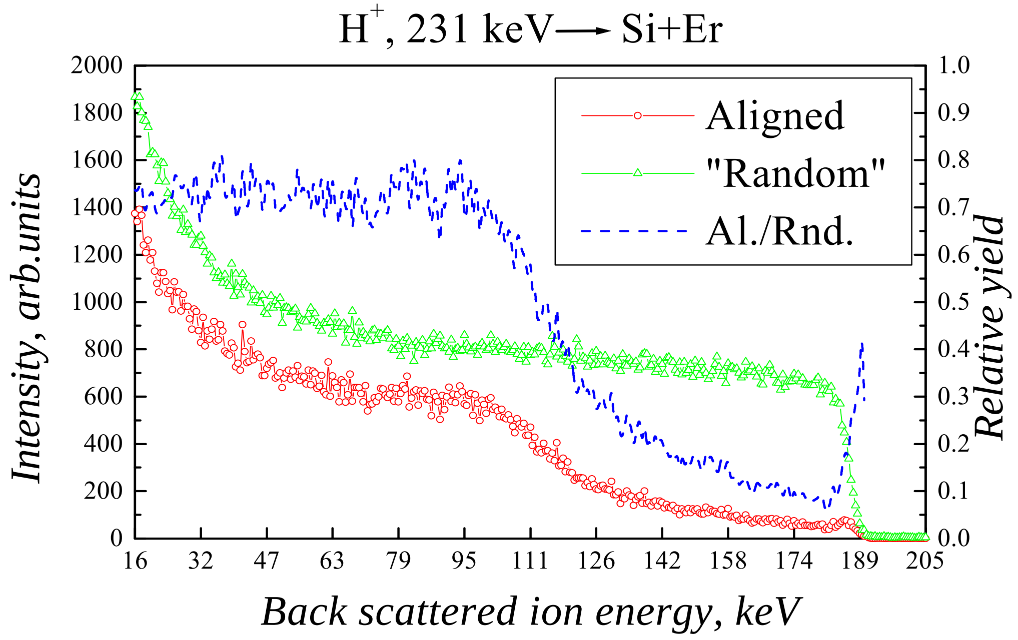
(Si_{pol}(m=30)/Si_{mon}) sample spectra

H^+, 190 keV, ESA

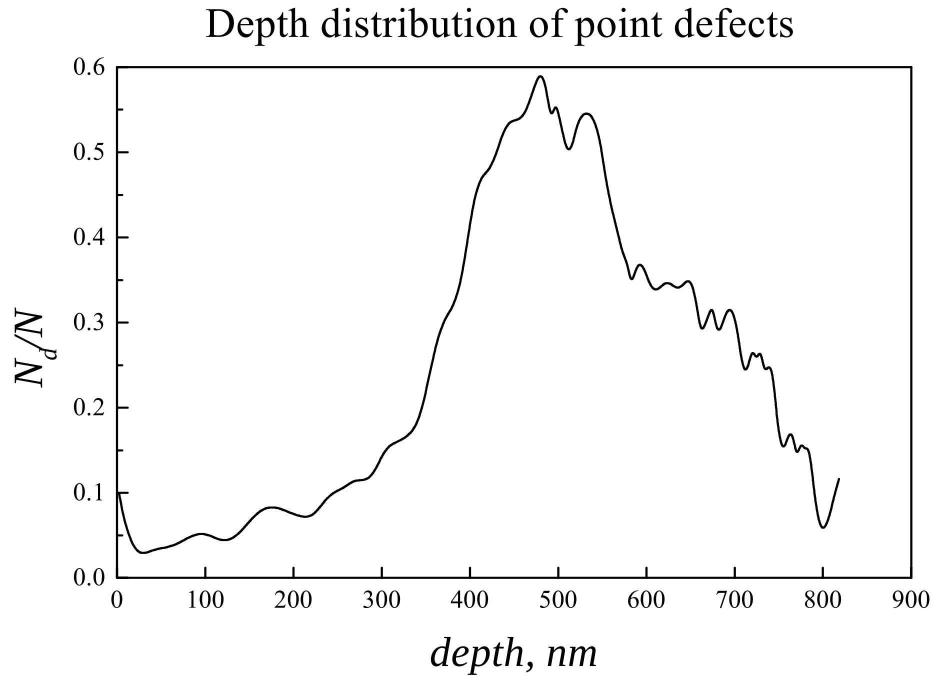
$Si/Si_xGe_{1-x}/Si$ structure spectrum



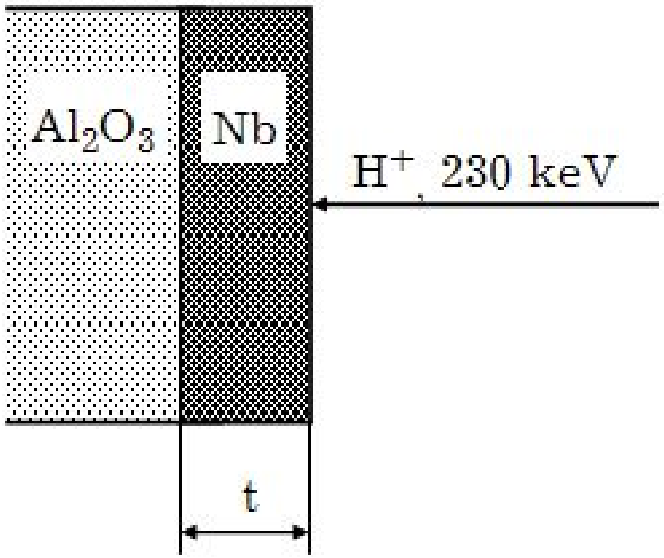

Intesity, arb. units
Si
aligned
"random"
simulated
Ge
Ge
135
141
147
152
158
164
170
176
182
188
194
199
205
back scattered ion energy, keV
$n_{Ge}/(n_{Si}+n_{Ge})$
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
5
10
15
20
25
30
35
40
45
50
depth, nm
He+,
230 keV
Si
Si
Si
Ge,
1 ml



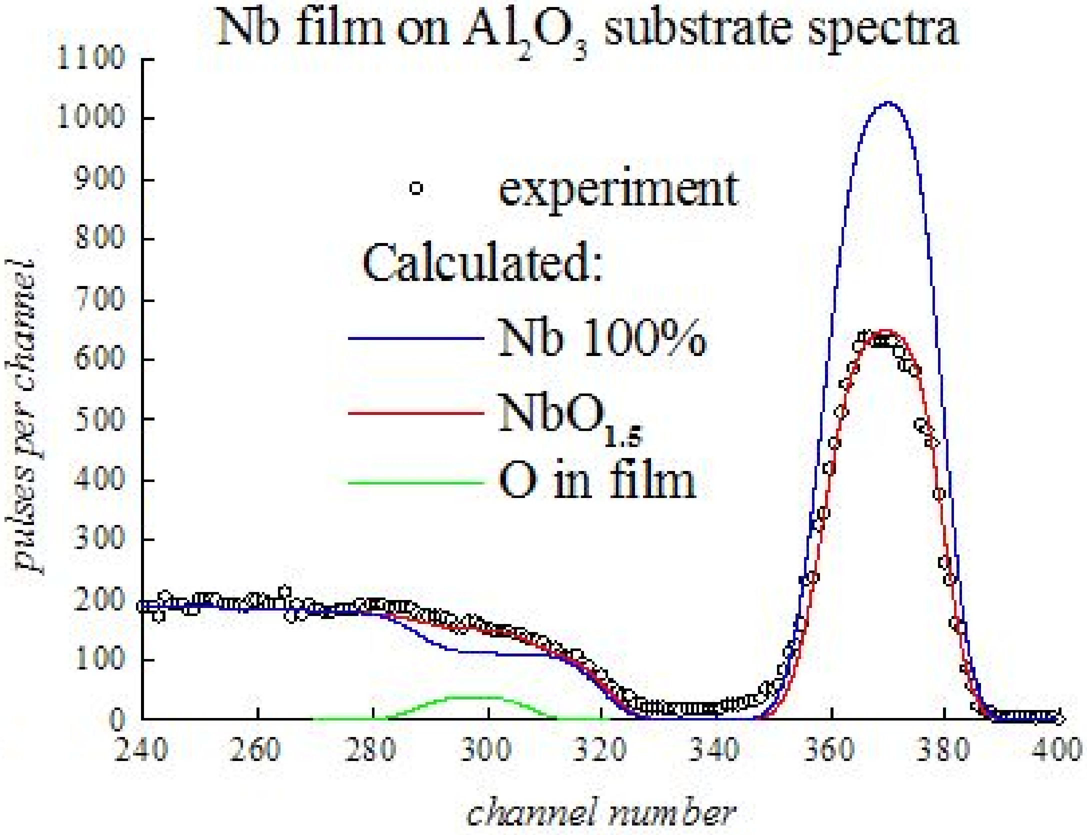
H$^+$, 231 keV ⟶ Si+Er

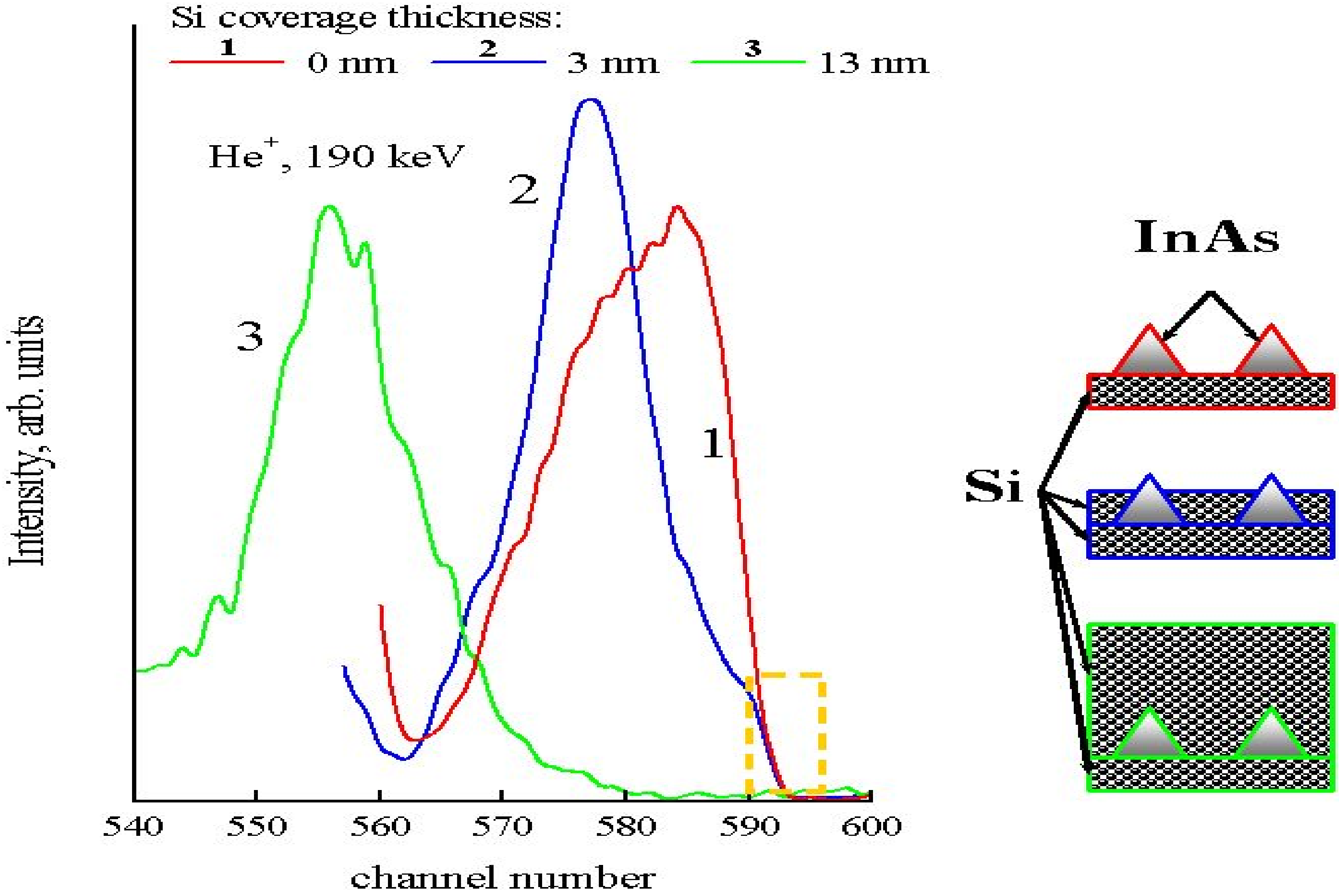


Depth distribution of point defects

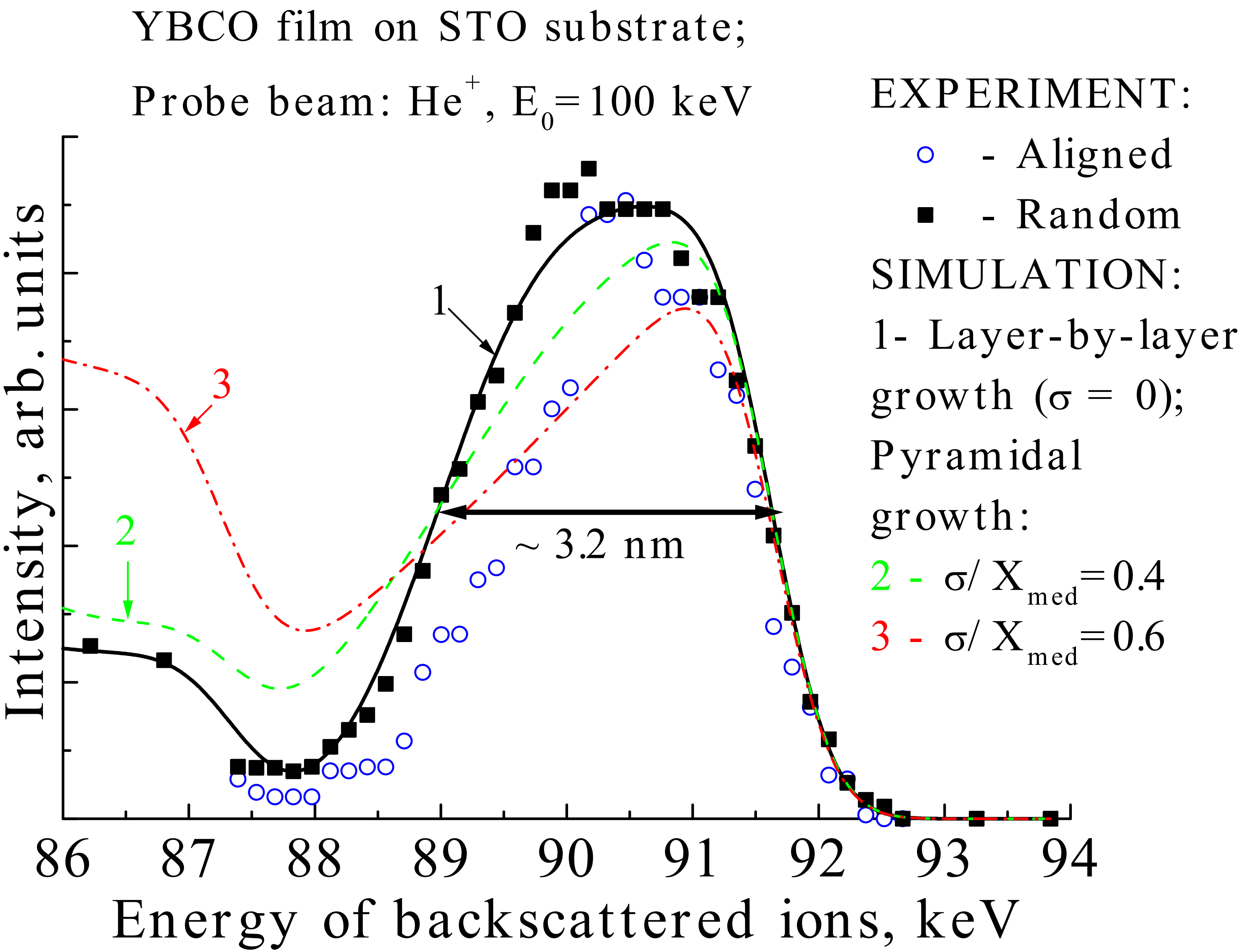


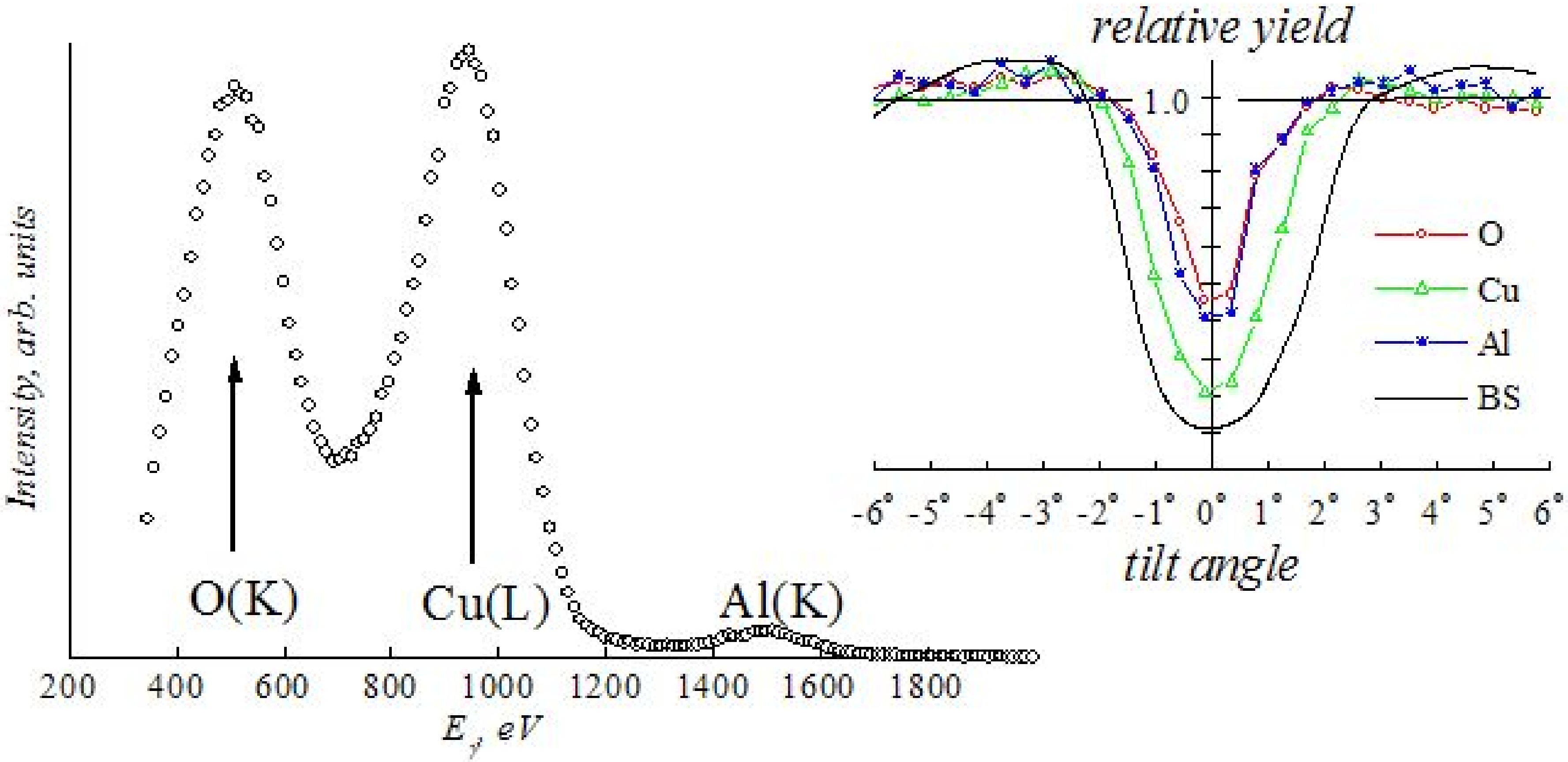
$t = 88 \cdot 10^{15}$ mol./cm^2 $\cong$ 260 Å



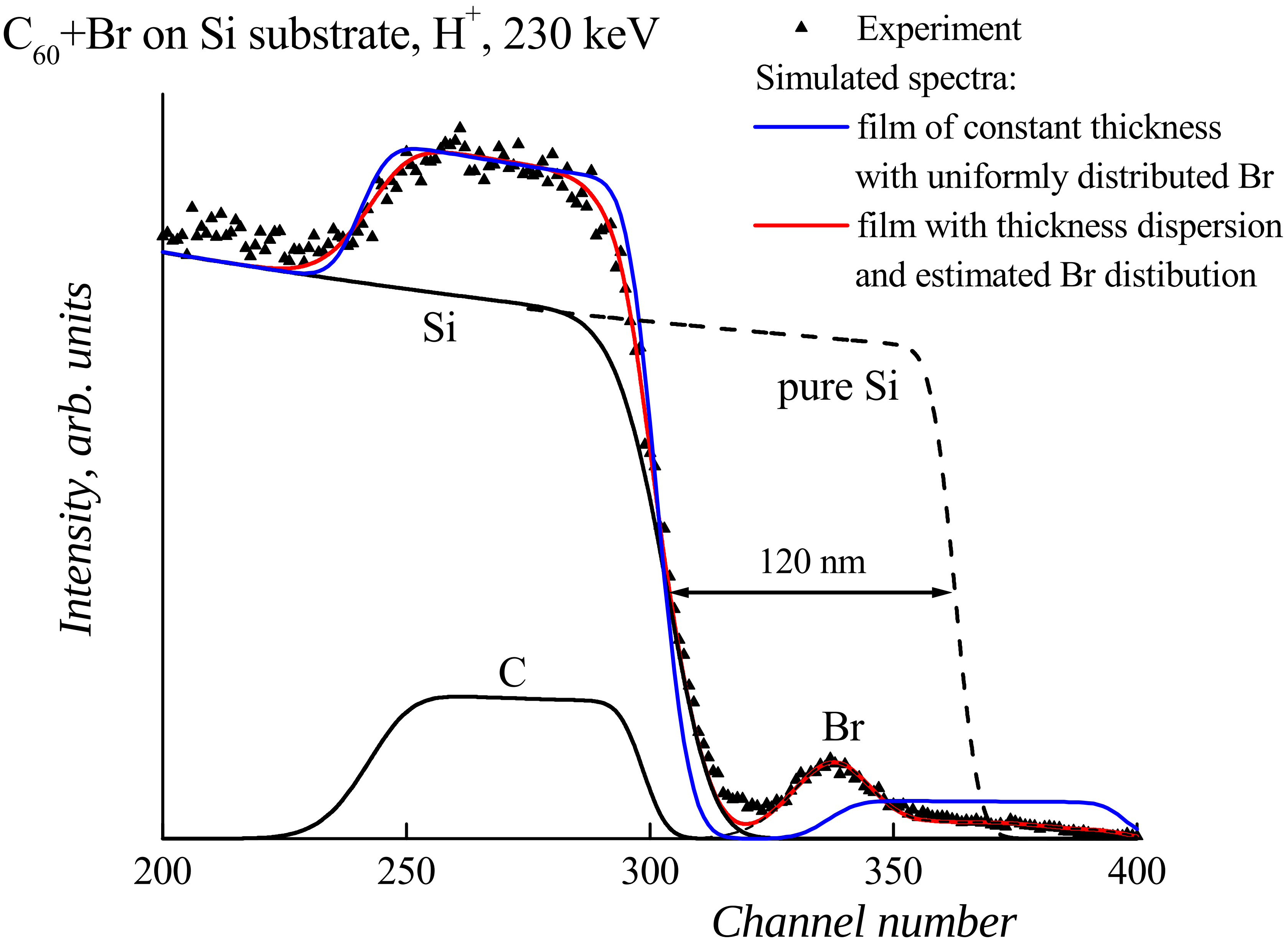


Fragments (In peaks) of Si/InAs/Si system for three different Si coverage thicknesses.


YBCO film on STO substrate;
Probe beam: He^+, E_0=100 keV
EXPERIMENT:
○ - Aligned
■ - Random
SIMULATION:
1- Layer-by-layer growth (σ = 0);
Pyramidal growth:
2 - σ/X_{med}=0.4
3 - σ/X_{med}=0.6
1
2
3
~ 3.2 nm
Intensity, arb. units
86
87
88
89
90
91
92
93
94
Energy of backscattered ions, keV

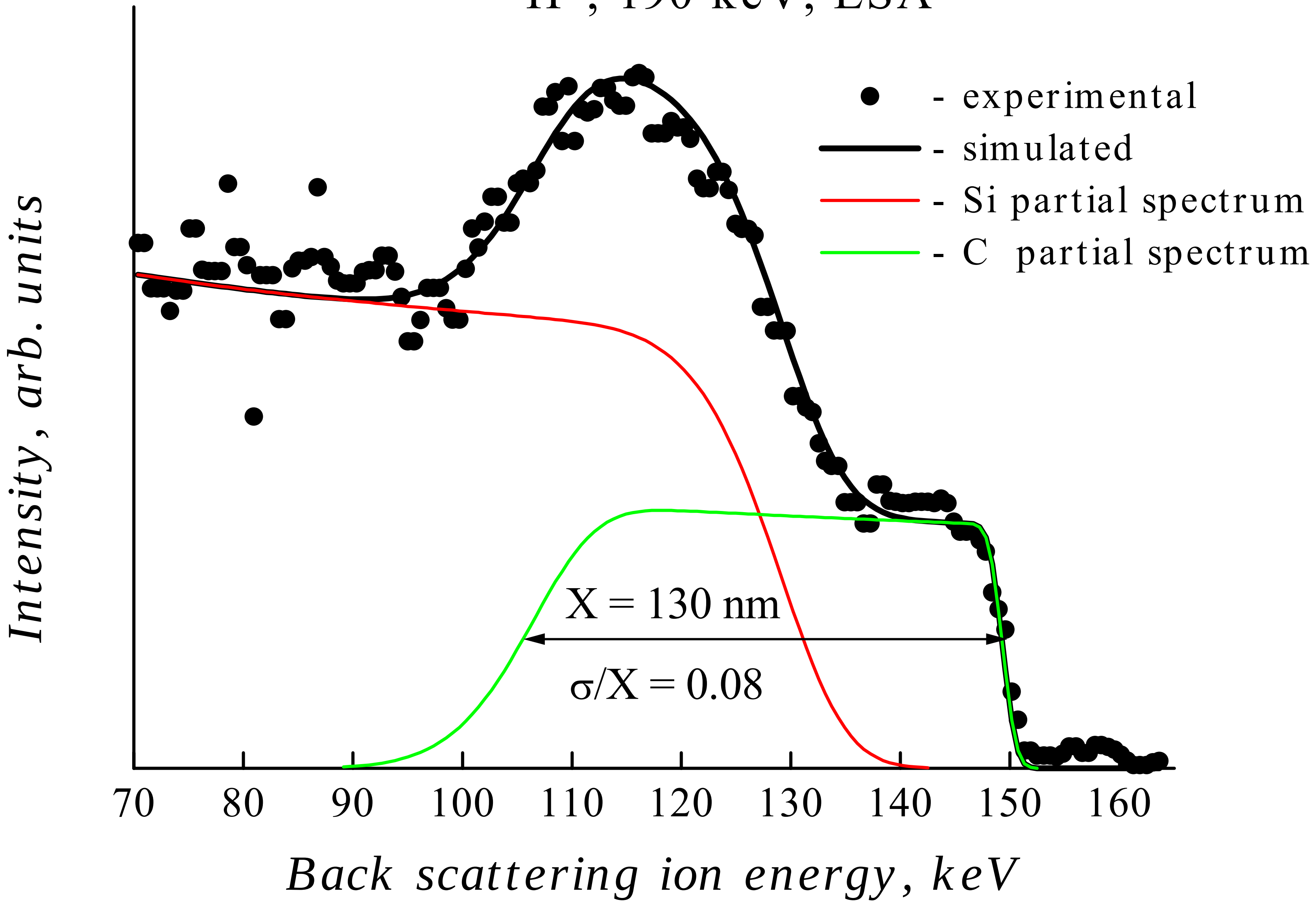


PIXE spectrum of $NdBa_2Cu_3O_7$ with presence of Al impurity. Angular scans for back scattered ions (BS) and 3 X ray emission lines.

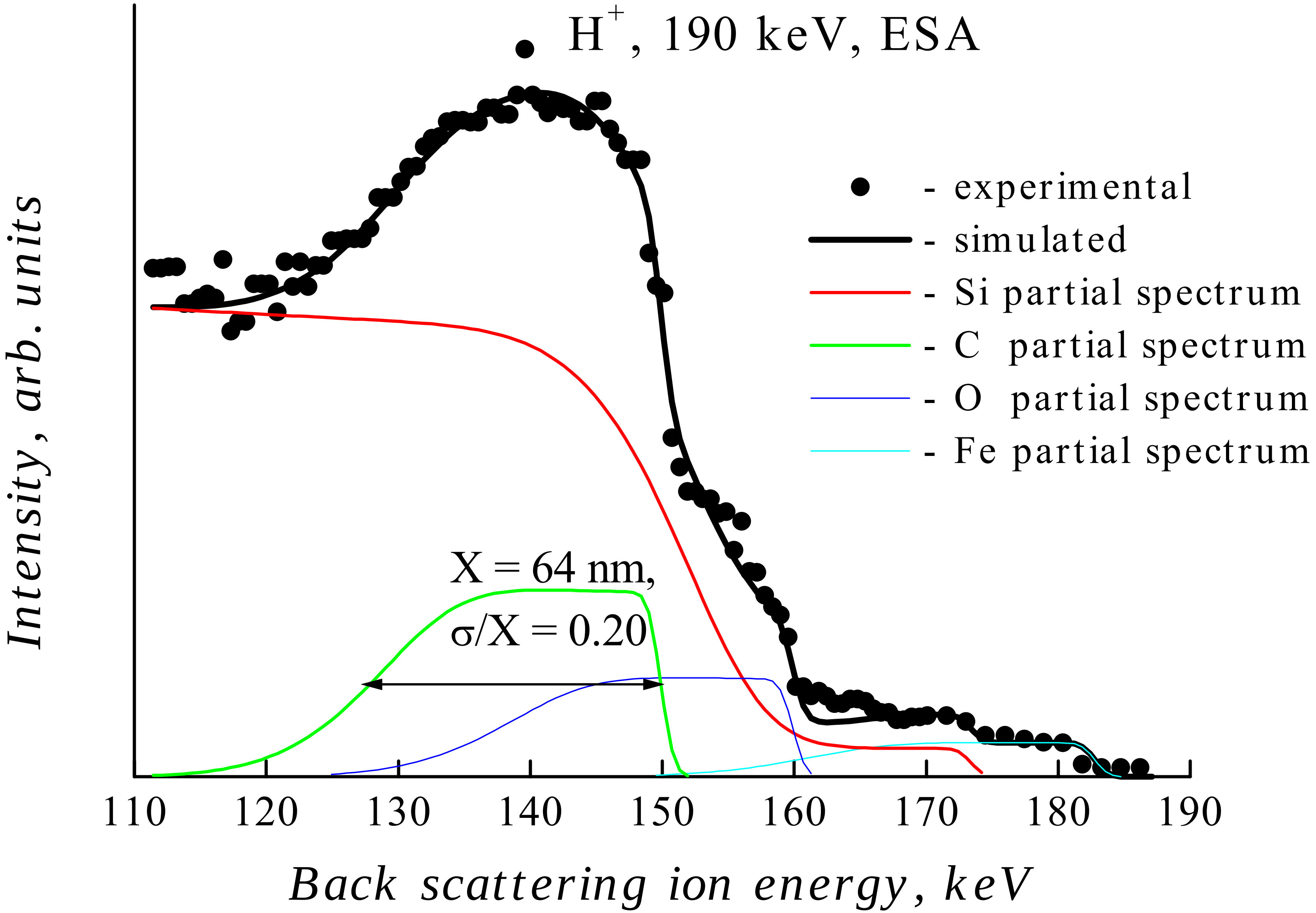

C60+Br on Si substrate, H+, 230 keV
Experiment
Simulated spectra:
film of constant thickness with uniformly distributed Br
film with thickness dispersion and estimated Br distibution
Si
pure Si
120 nm
C
Br
Intensity, arb. units
Channel number
200
250
300
350
400

Sample C-60 (Si substrare), aligned regime

H^+, 190 keV, ESA



Sample C-60lv (Si substrare), aligned regime (after vacuum lazer irradiation and etching)



Aligned spectra of detonation nanodiamonds, deposited on Si substrate. H^+, 230 keV, ESA