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Study of surface reflection of high energy protons from solids at PNPI

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Participants

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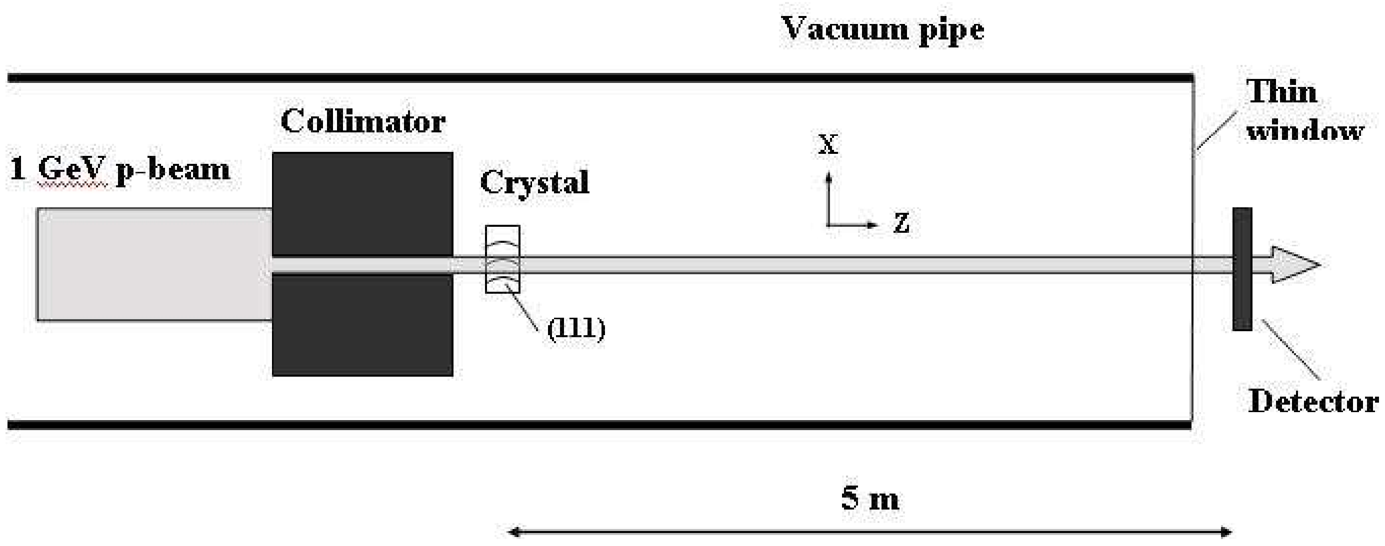
Motivation

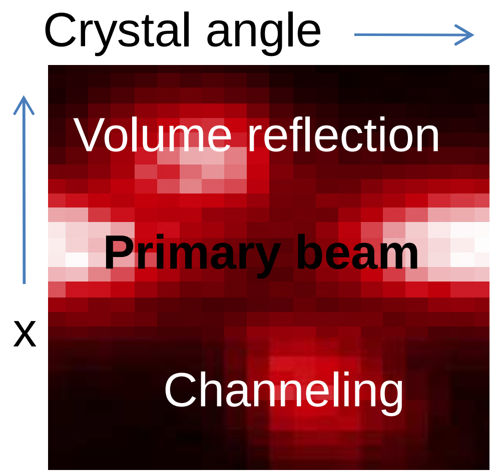
- The joint studies at CERN in frames of H8-RD22 and UA9 collaborations resulted in development of new types of beam crystal deflectors based on channeling and volume reflection effects and made possible to start preparation of experiment on beam crystal collimation at LHC (LUA9 Project).

- In the collider, the circulating high energy particle beam spreads very slowly to the targets restricting the aperture of beam pipe (collimator, crystal etc.), so the first interaction of halo particle with the target takes place in the surface layer.

- The present study was done to clarify this interaction.

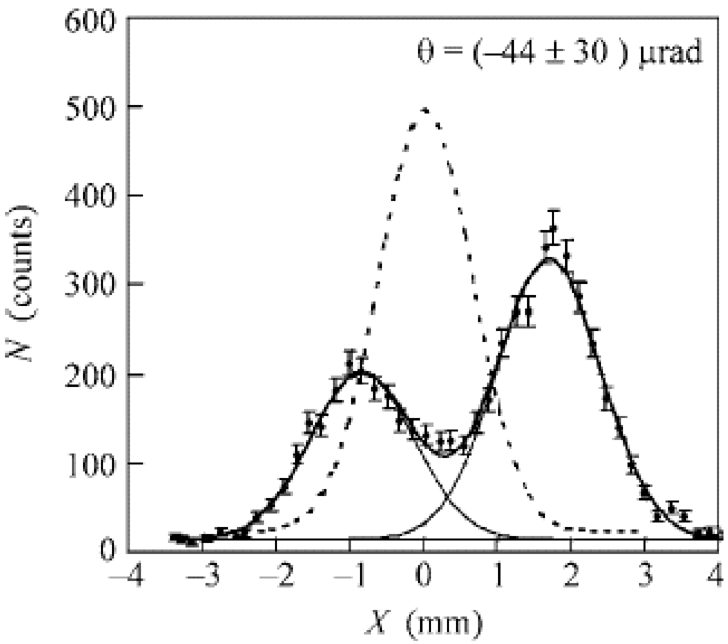
Experimental layout at PNPI



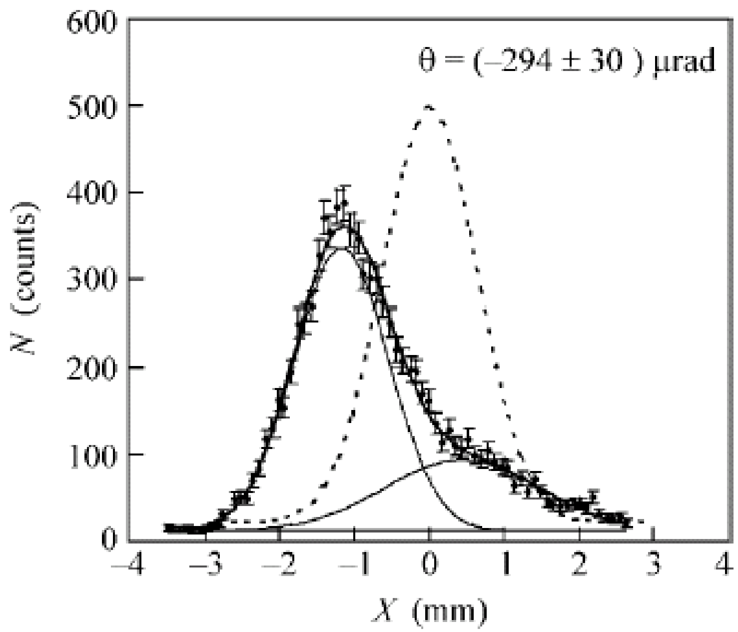


We used the same layout as described in:
Yu.M.Ivanov et al., Volume Reflection of 1 GeV Protons by a Bent Silicon Crystal, JETP Letters, 2006, Vol. 84, No. 7, pp. 372–376.

Typical beam profiles measured with scintillator beam scanner in VR study



Beam profile in the angular position of the crystal that corresponds to the maximum channeling.



Beam profile in the angular position of the crystal that corresponds to the maximum volume reflection.

Result for volume reflection of 1 GeV protons from bent (111) silicon planes

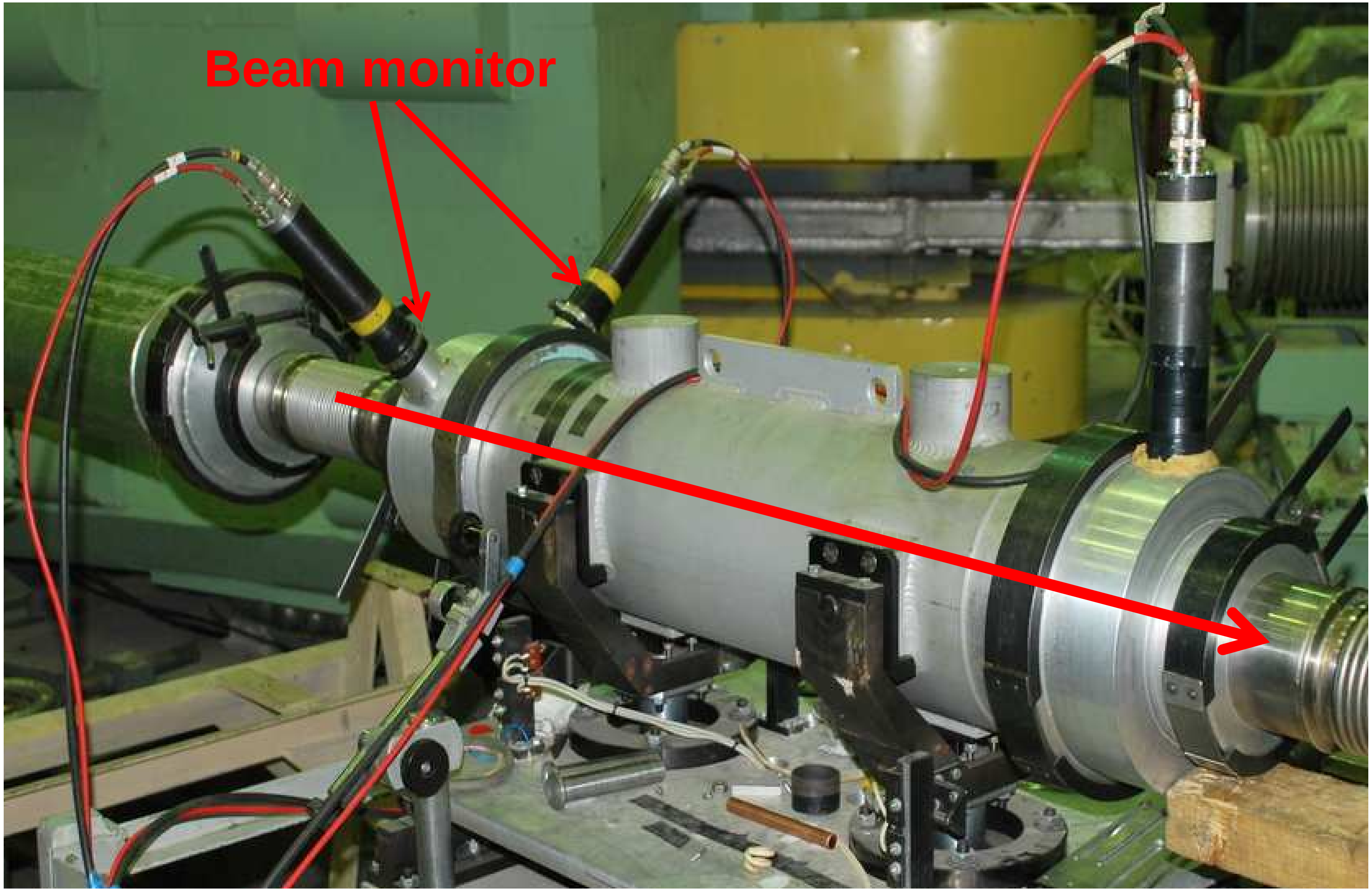
Probability of the volume reflection:

$$P_R \sim 0.7$$

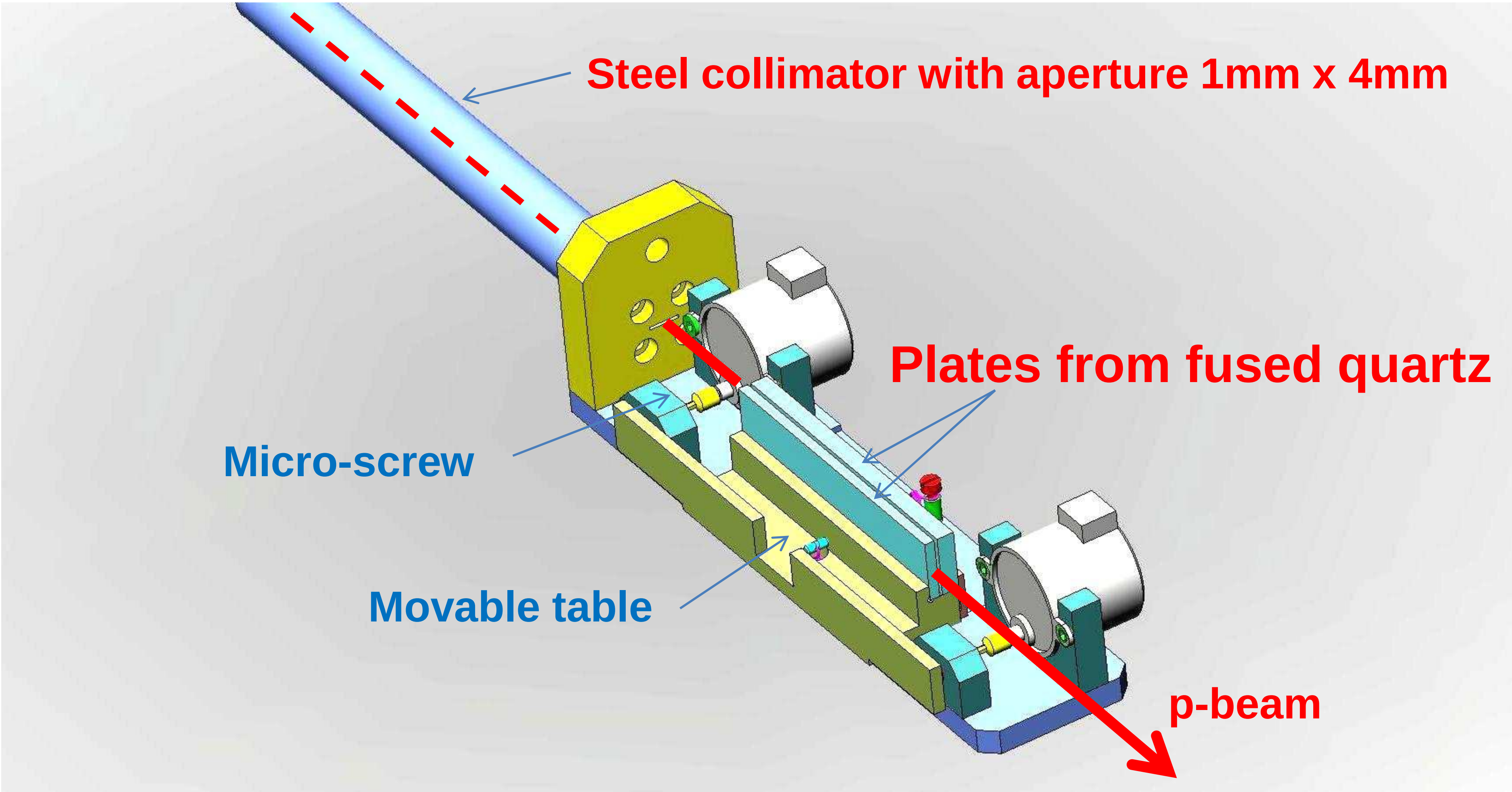
Mean deflection angle of volume reflected protons:

$$2\theta_R \sim 240\ \mu\text{rad} = 1.4 \cdot \theta_c$$

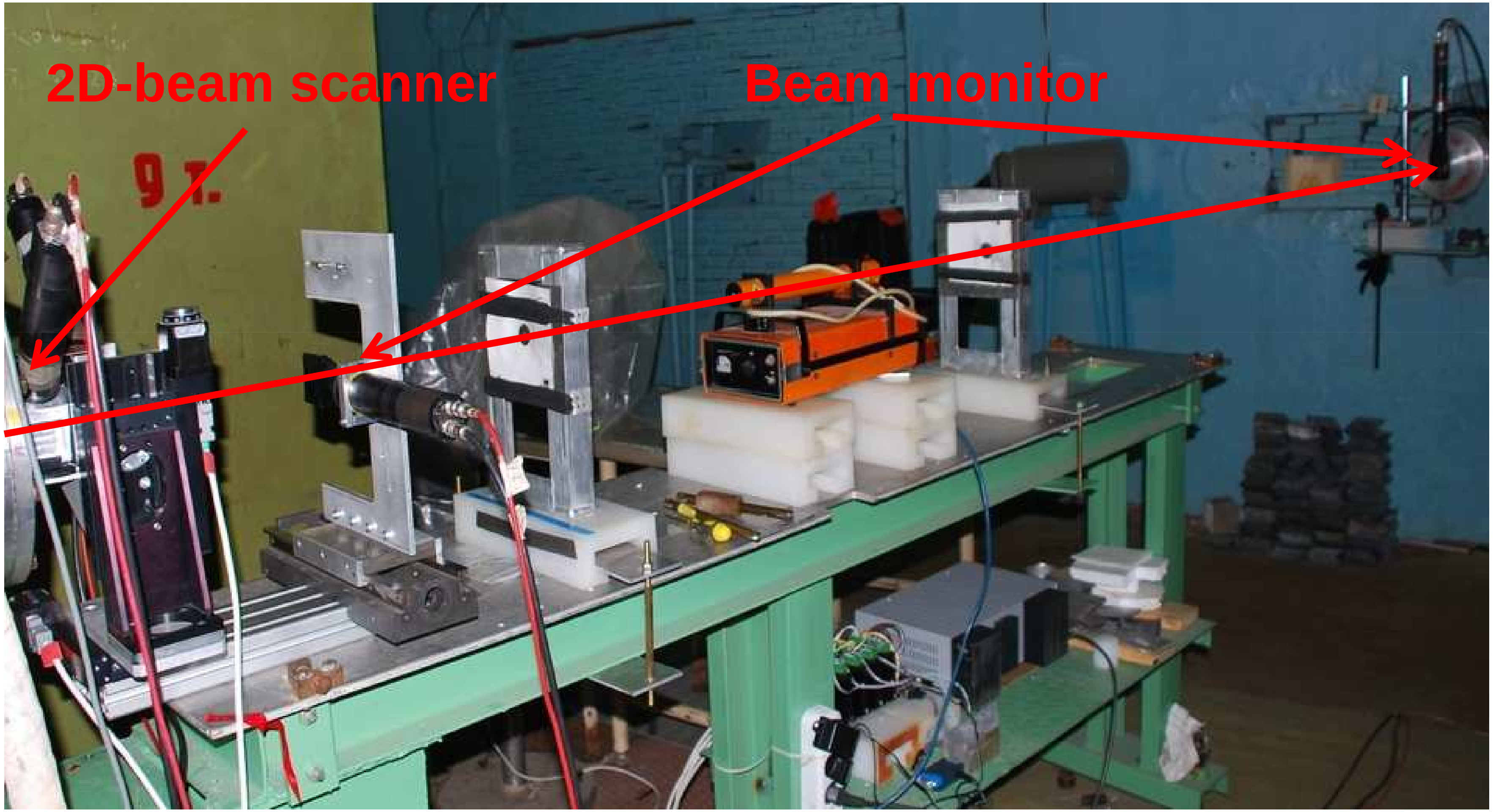
Upgraded collimator



New 2-linear motion stage with samples



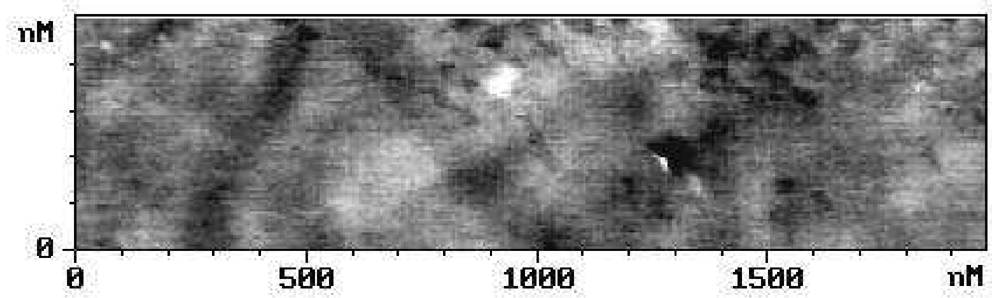
Detector system

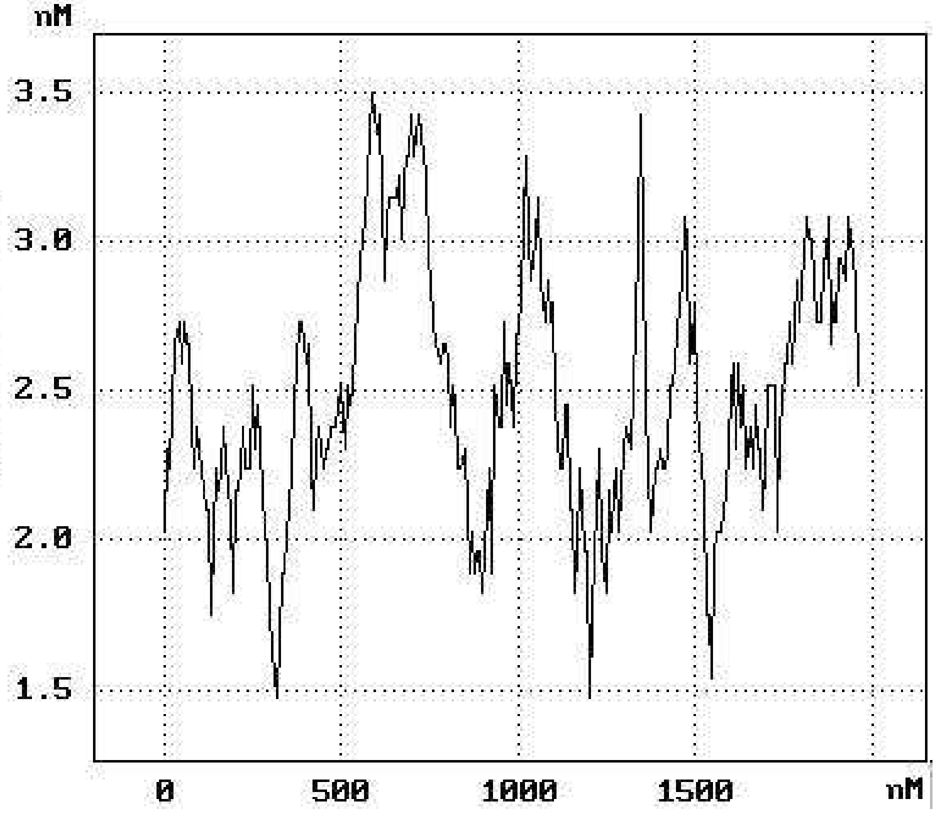


Experimental details

Beam divergence:	30 – 100 µrad
Aperture of collimator:	1mm x 4mm
Material of plates:	fused quartz
Sizes of plates:	8mm x 20mm x 100mm
Flatness of plates:	~ 0.1 µm
Width of gap between plates:	~ 15 µm
Angular range:	± 300 microradians
Sensitive area of beam scanner:	85µm x 850 µm

Roughness of fused quartz plate surface measured with AFM





Rmax = 6.23 nm

Result for surface reflection of 1 GeV protons from quartz plate

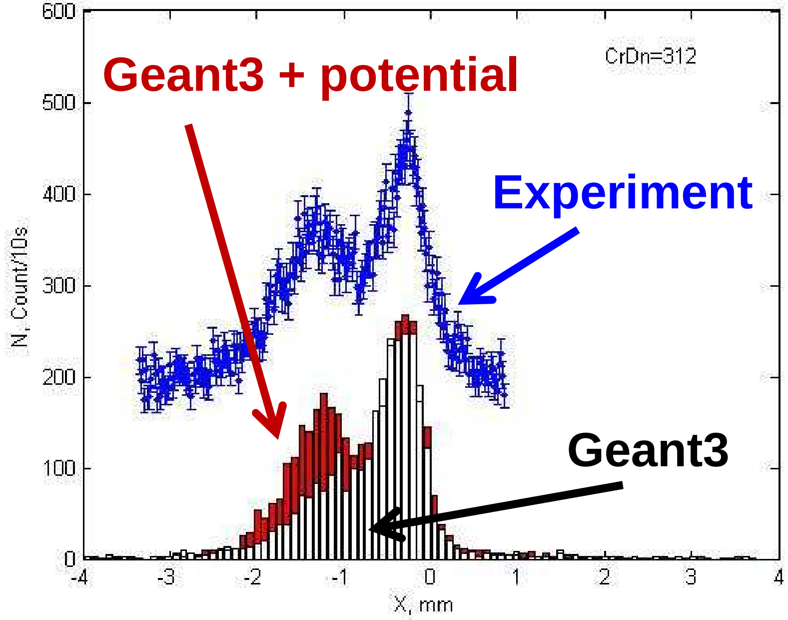
For probability of the surface reflection: ***~ 0.7***

Mean deflection angle of surface reflected protons: ~ 260μrad

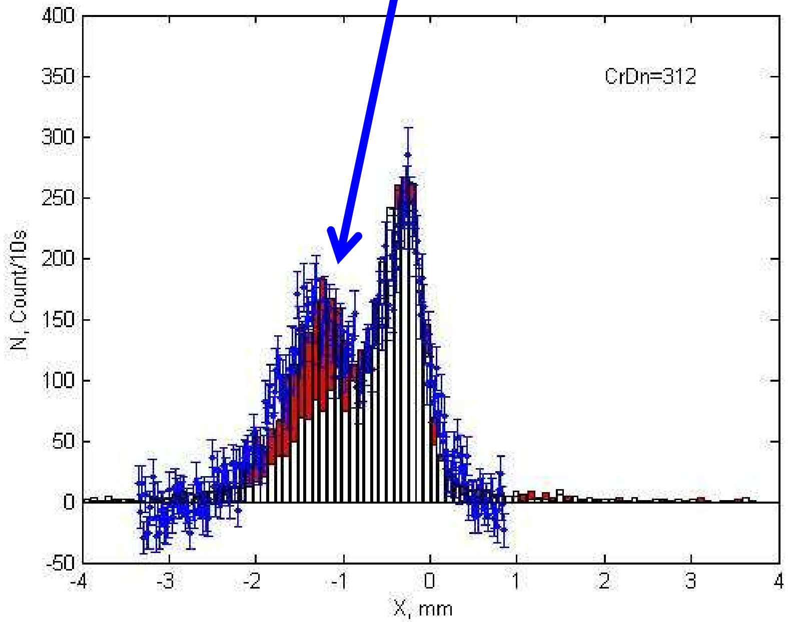
It is comparable with volume reflection case!

- **This result can not be explained by multiple Coulomb scattering.**
- **But it can be described in the approximation of continuous potential.**

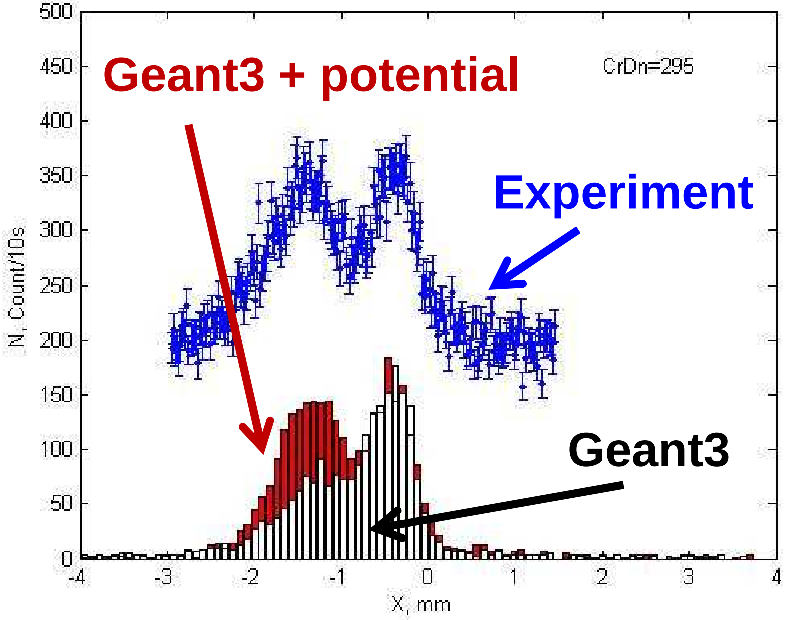
X-scan of beam with quartz under 130 microradians to incident beam



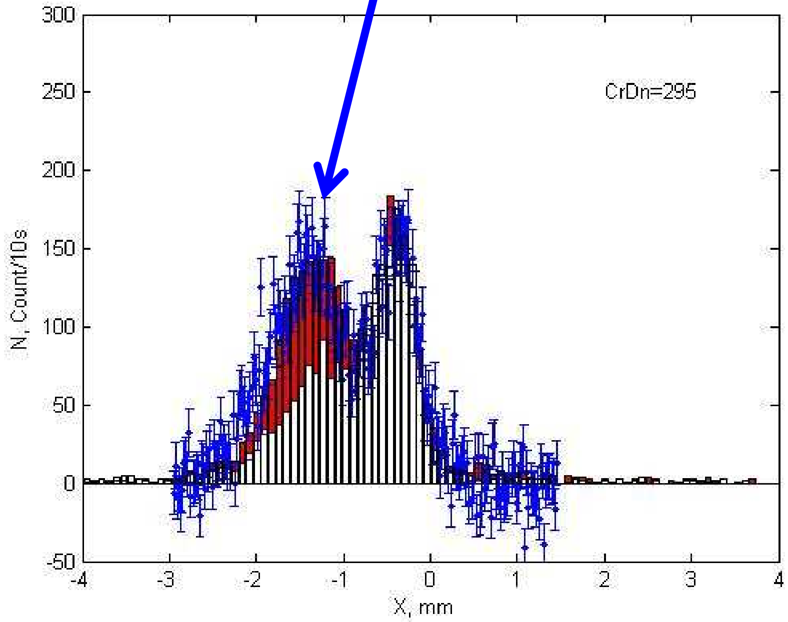
Experimental plot with subtracted background



X-scan of beam with quartz under 150 microradians to incident beam



Experimental plot with subtracted background



Thomas-Fermi potential

$$V(r) = (Z_1 Z_2 e^2/r)\varphi(r/a),$$

where $\varphi(r/a)$ is a screening function of Thomas–Fermi type and a is a screening length characteristic of any two given collision partners.

Moliere potential

An explicit analytical form does not exist for the Thomas–Fermi screening function: it can be expressed only in the form of a differential equation . However, there exists a good analytical approximation due to Molière

$$\varphi(r/a) = \sum_{i=1}^{3} \alpha_i \exp(-\beta_i r/a),$$

where $\{\alpha_i\} = \{0.1, 0.55, 0.35\}$ and $\{\beta_i\} = \{6.0, 1.2, 0.3\}$

$$a = (9\pi^2/128\ Z_2)^{1/3}(\hbar^2/m_e e^2) = 0.8853 a_0 Z_2^{-1/3}$$

a_0 is the Bohr radius

Atomic plane potential

$$V_{PS}(\rho) = n \int_0^{\infty} 2\pi R\, dR\, V[(\rho^2 + R^2)^{1/2}]$$

$$= 2\pi n Z_1 Z_2 e^2 a f_{PS}(\rho/a)$$

where n is the areal density of atoms in the plane

$$f_{PS}(\xi) = \sum_{i=1}^{3} (\alpha_i/\beta_i)\exp(-\beta_i \xi)$$

Planar potential in crystal

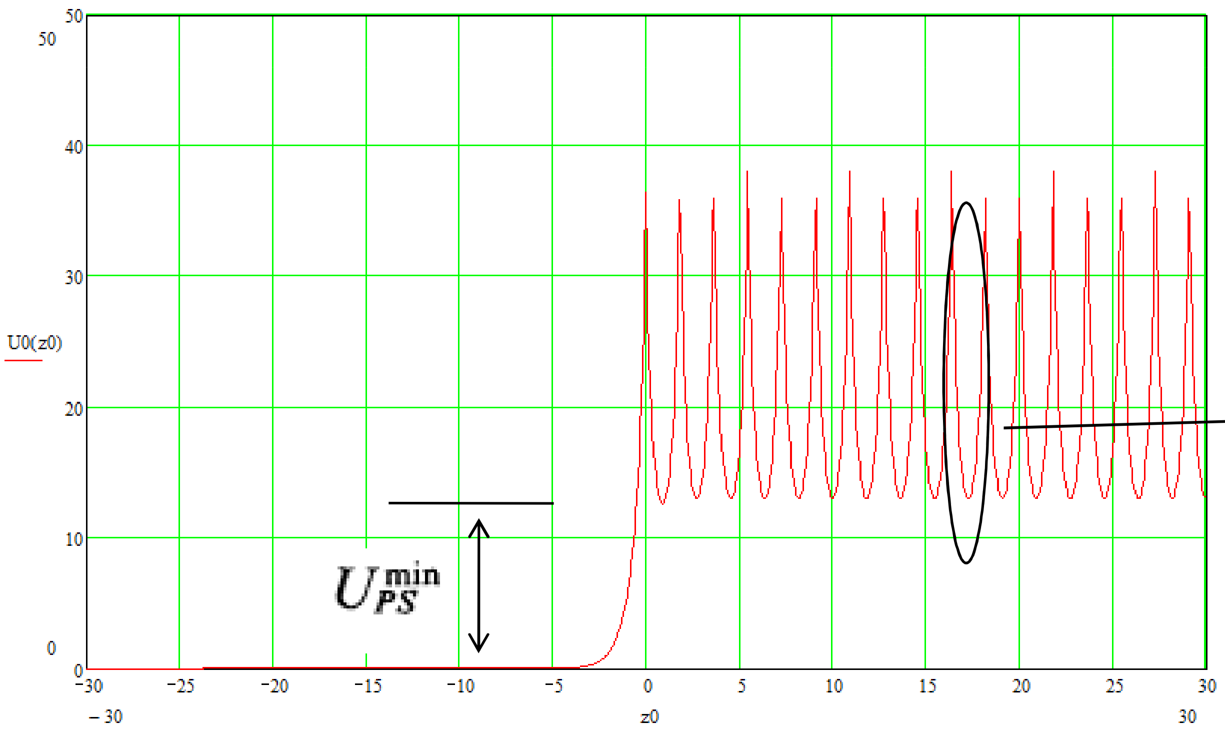
Similarly, for planes, one has

$$U_{PS}(z) = \sum_i V_{PS}(|z - z_i|) - U_{PS}^{\min},$$

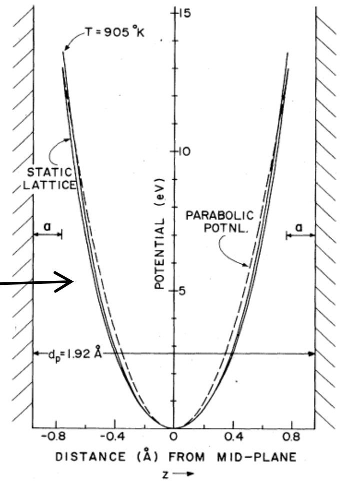
where z and z_i are measured in a line normal to the set of planes being studied.

Continuous potential near ideal edge of silicon crystal without miscut

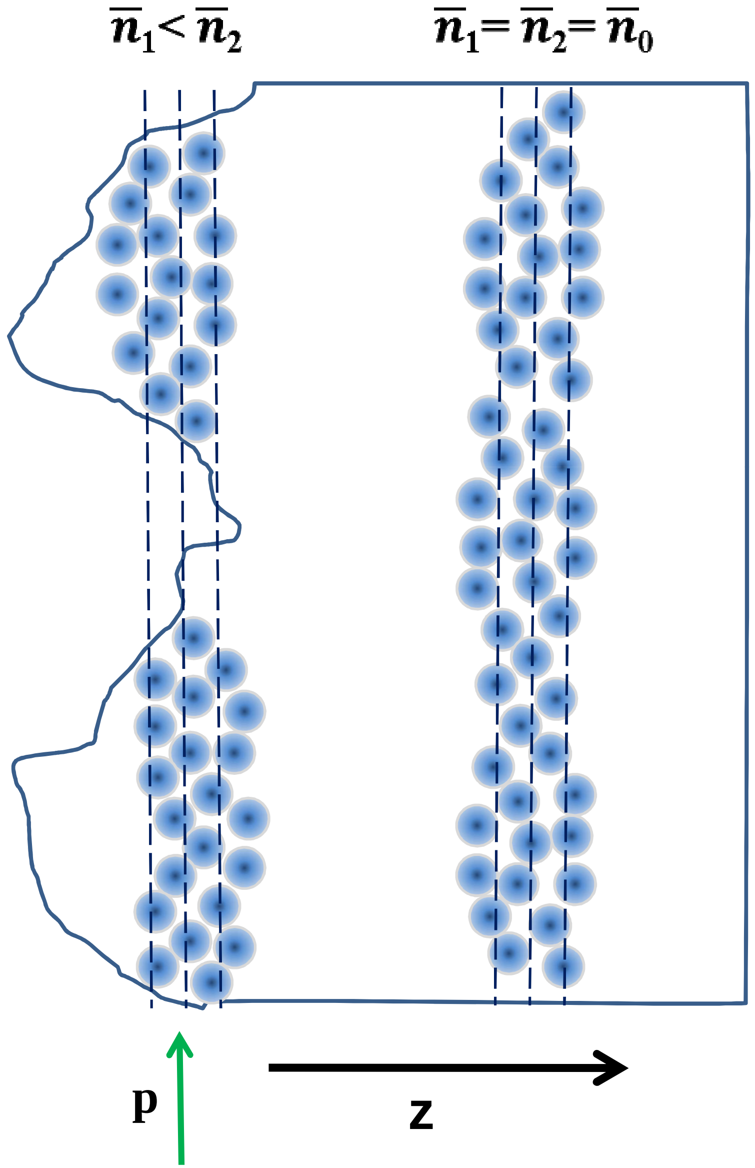
$$U0(z0) := 2\pi \cdot Z1 \cdot Z2 \cdot ee \cdot aa \cdot nn \cdot \left[\sum_i \left[\left(\frac{a1}{b1}\cdot \exp\left(\frac{-b1\cdot |z0 - z(i)|}{aa}\right)\right) + \left(\frac{a2}{b2}\cdot \exp\left(\frac{-b2\cdot |z0 - z(i)|}{aa}\right)\right) + \left(\frac{a3}{b3}\cdot \exp\left(\frac{-b3\cdot |z0 - z(i)|}{aa}\right)\right)\right]\right]$$

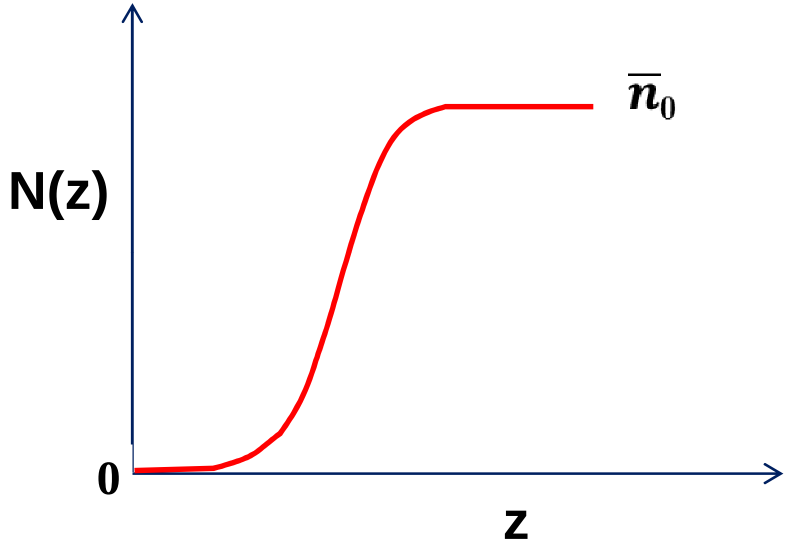


Channeling potential



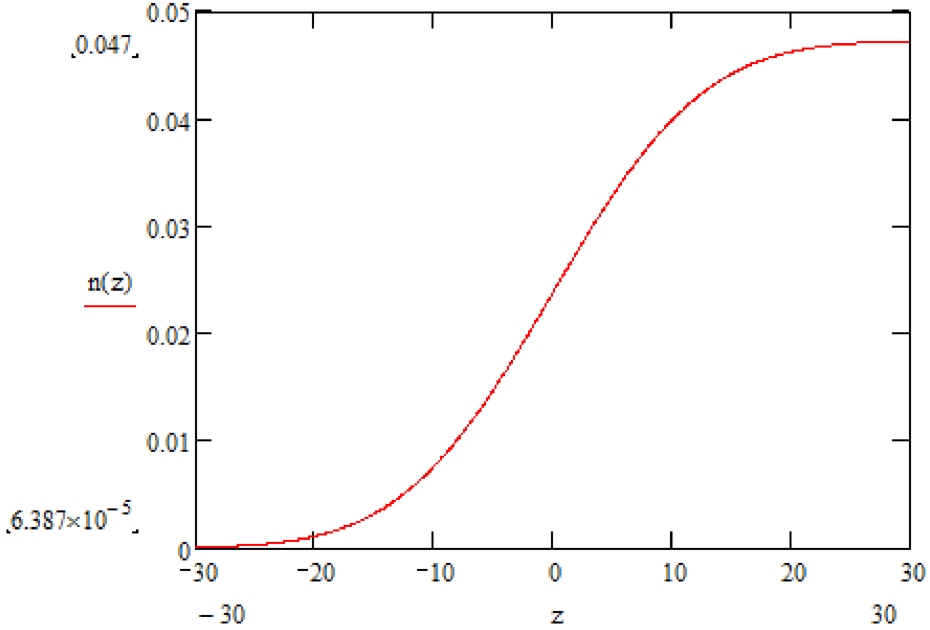
Effective density n(z) for high energy proton moving parallel to the solid surface





Effective density of surface layer with pnorm()-function

$$n(z) := \rho 2 \cdot \frac{N0}{A2} \cdot 10^{-24}\, \mathrm{pnorm}(z, 0, 10)$$

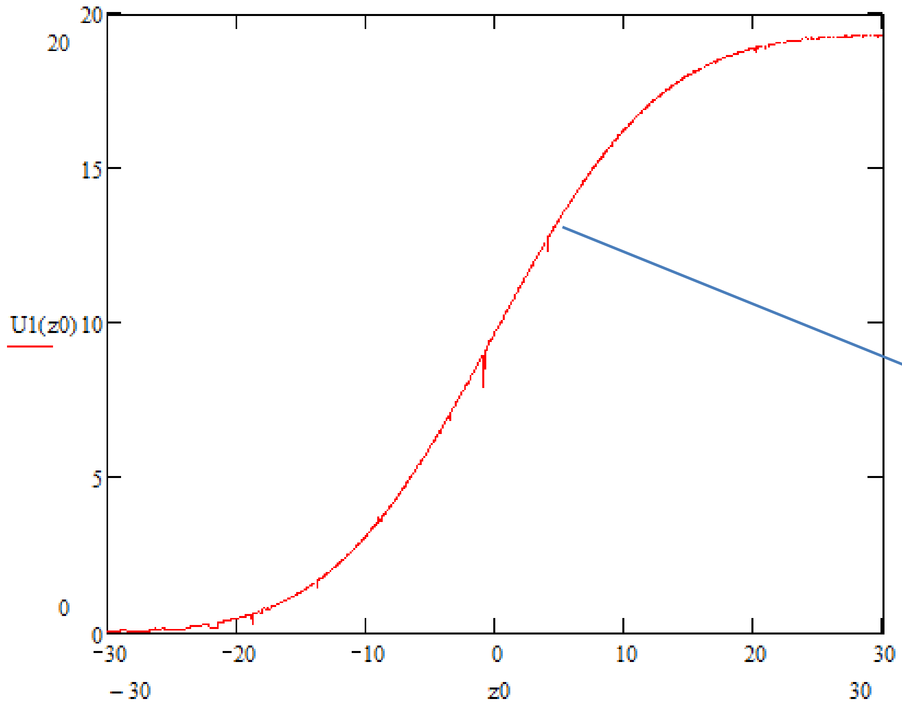


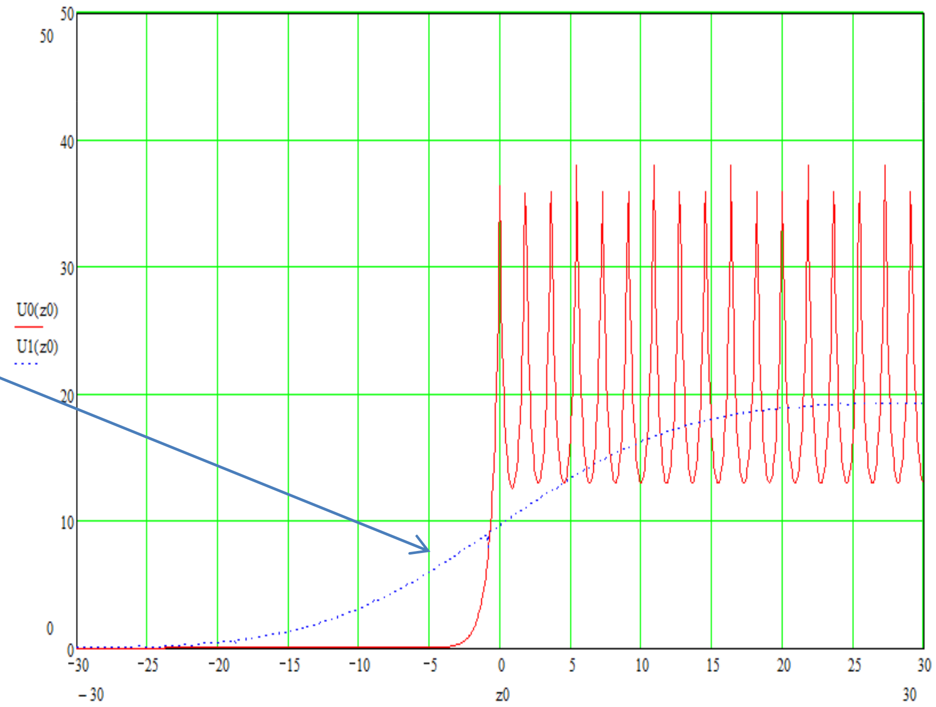
Potential in surface layer for amorphous silicon. Comparison with crystalline silicon

$$U1(z0) := 2\pi \cdot Z1 \cdot Z2 \cdot ee \cdot aa \cdot \int_{-40}^{40} n(z) \cdot \left[\left(\frac{a1}{b1} \cdot \exp\left(\frac{-b1 \cdot |z0 - z|}{aa}\right)\right) + \left(\frac{a2}{b2} \cdot \exp\left(\frac{-b2 \cdot |z0 - z|}{aa}\right)\right) + \left(\frac{a3}{b3} \cdot \exp\left(\frac{-b3 \cdot |z0 - z|}{aa}\right)\right)\right] dz$$

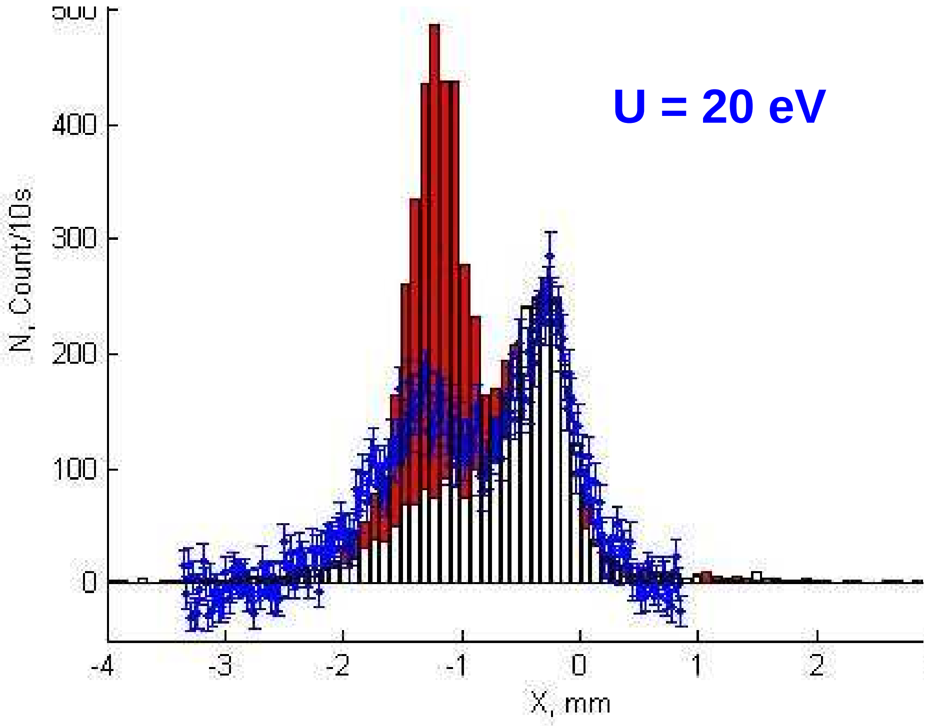
Amorphous silicon

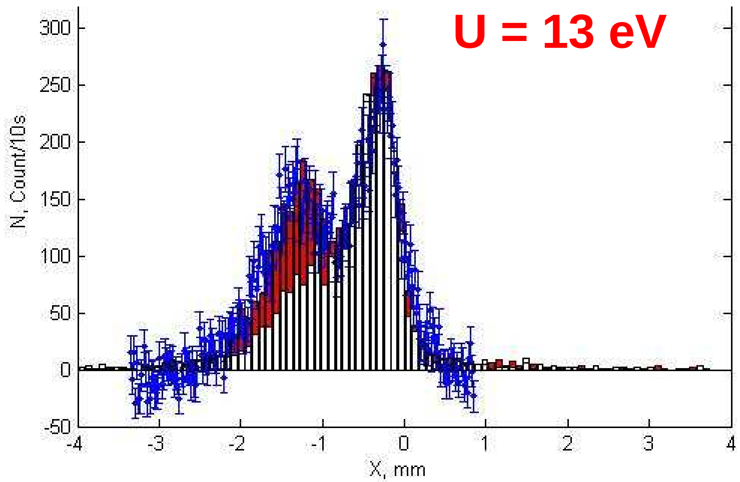
Crystalline silicon

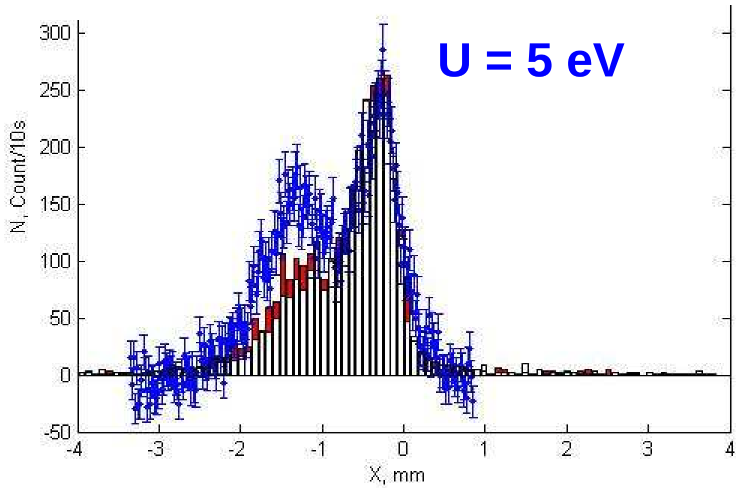




Geant3 calculations with different values of effective potential







Estimation of effective potential

$U \approx 13$ eV

It corresponds to the effective electric field in the surface layer of 10 nm thickness

$E \approx 13$ Megavolts / cm

Conclusions

- We have found that solid surface with roughness which is much more than atomic distance well reflects high energy protons.

- This reflection can not be explained by multiple scattering.

- But it can be described with the model of continuous potential.

- The origin of the potential step is density gradient across solid boundary.

- The value of the potential is in agreement with the value of internal potential of solids.