Experimental measurement of the enhancement of the nuclear interaction yield with crystalline targets

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Outline

- Introduction
- Orientational effects of charged particles in crystals
- Nuclear interaction probability under channeling
- Experiment at INFN Legnaro Laboratories
- Summary and conclusions

Introduction

- State of the art:

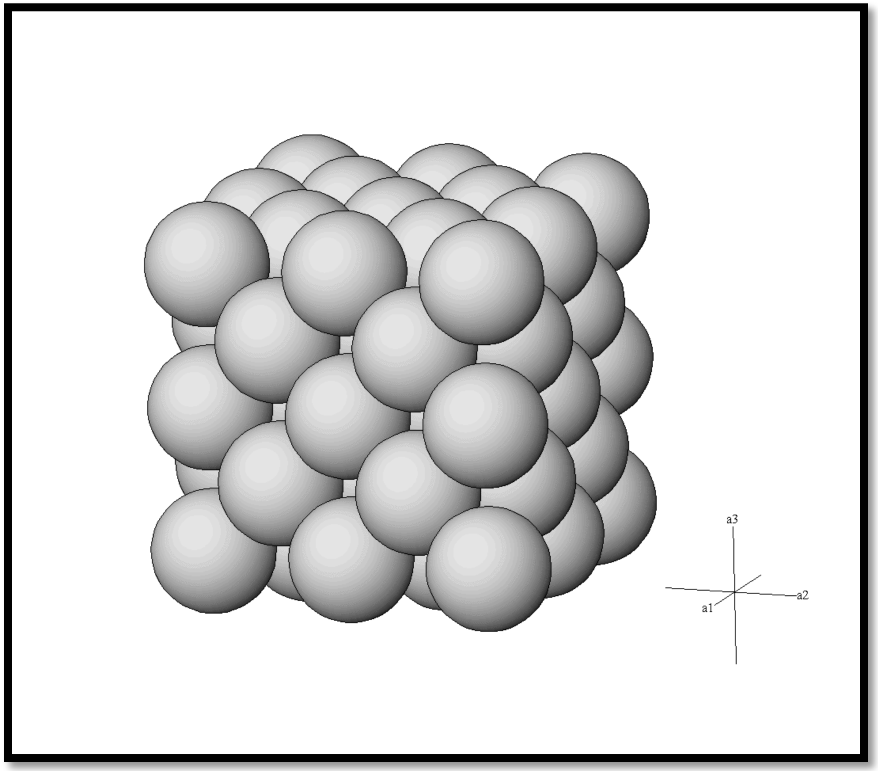
the availability of radio-isotopes is fundamental for diagnostic and therapeutic purposes in nuclear medicine.

- Aim:

enhancement of the radio-isotopes production yield through cyclotron with minor modification of current instrumentations.

- This work:

usage of microscopically ordered structures to force the particles to interact more frequently with nuclei.



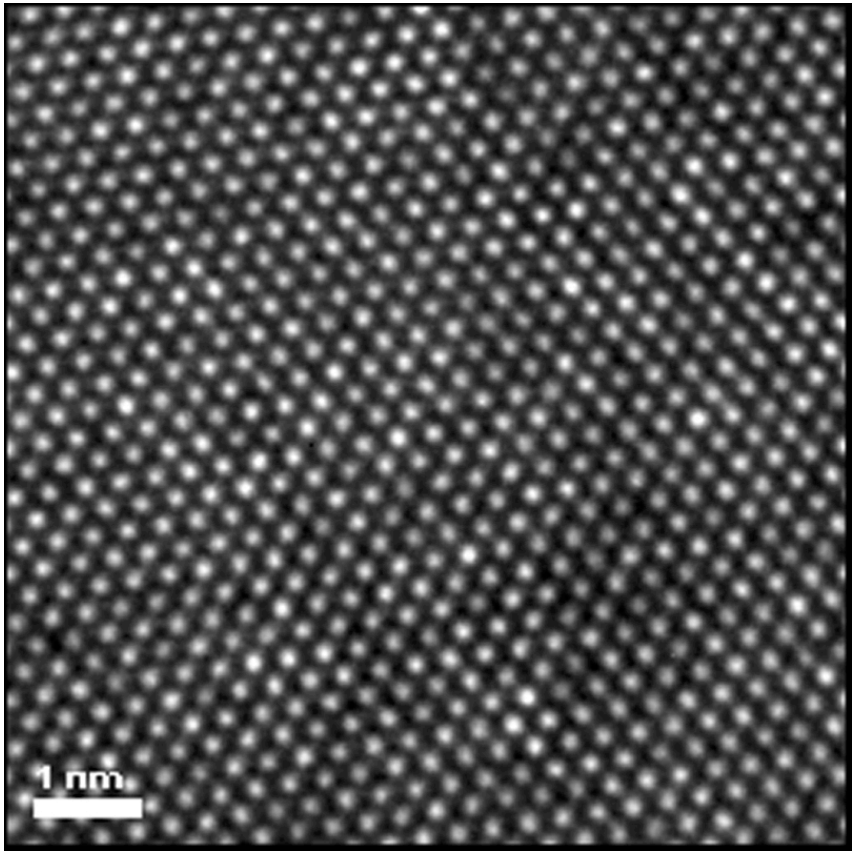
Orientational effects of charged particles in crystals

An introduction

Ordered Structure

- A crystal is a microscopically ordered pattern of atoms.

HRTEM image of a silicon (Si) [110] crystallographic zone axis.



Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396

Ordered Structure

- A crystal is a microscopically ordered pattern of atoms.
- Crystal planes are the geometric lines linking atoms.

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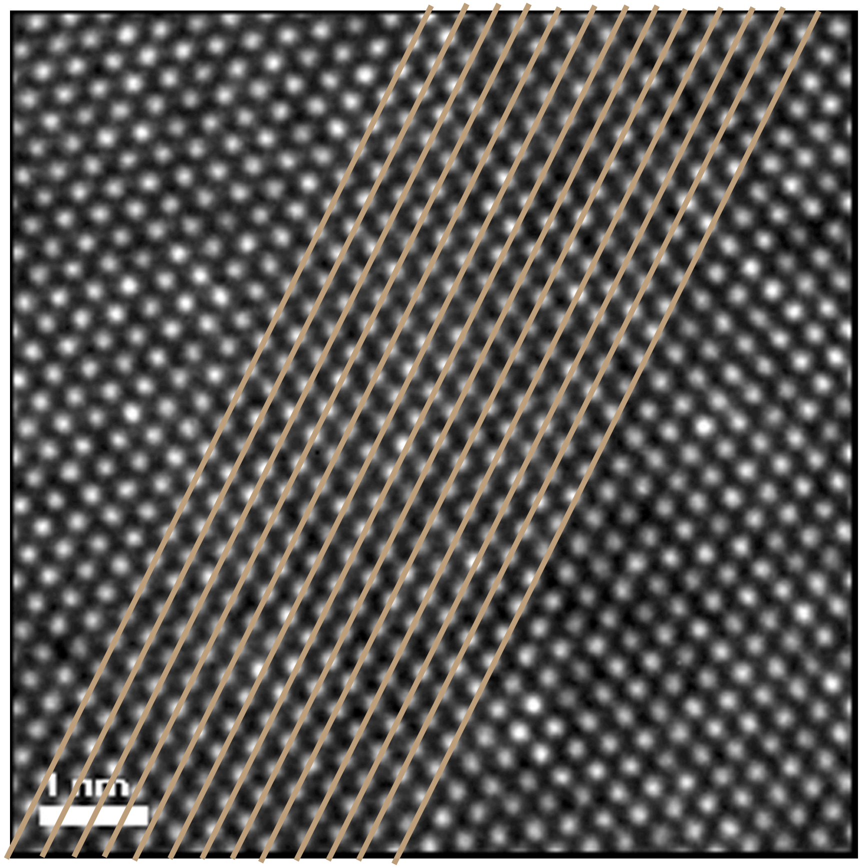
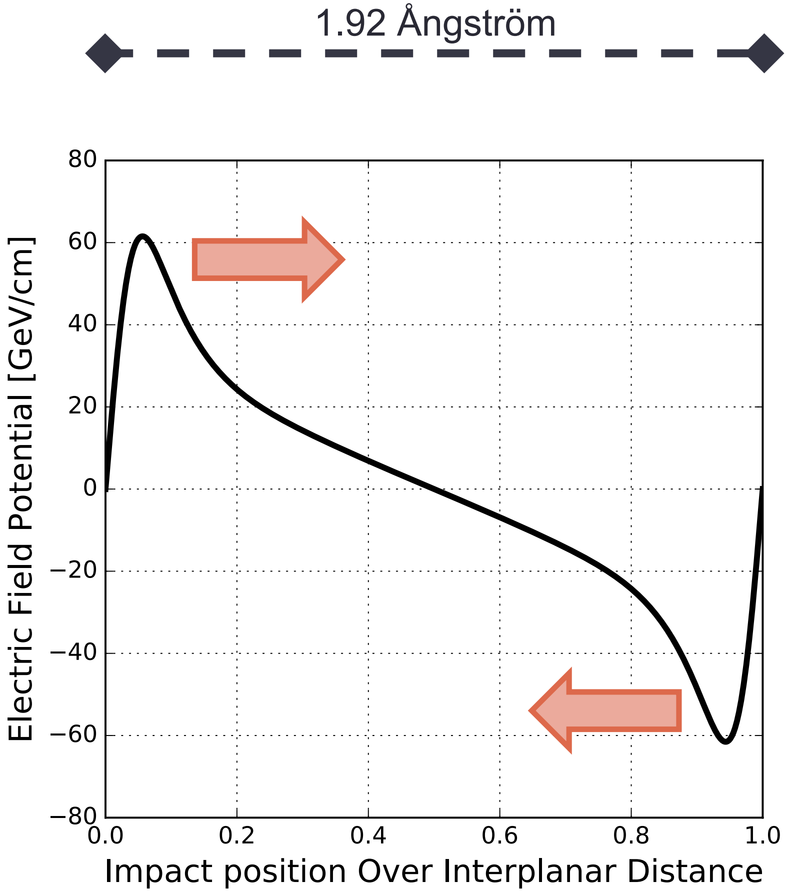


Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396

Ordered Structure

- A crystal is a microscopically ordered pattern of atoms.
- Crystal planes are the geometric lines linking atoms.
- Strong electromagnetic field between planes.

Inter-planar electric field for Si (110)



ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)

Ordered Structure

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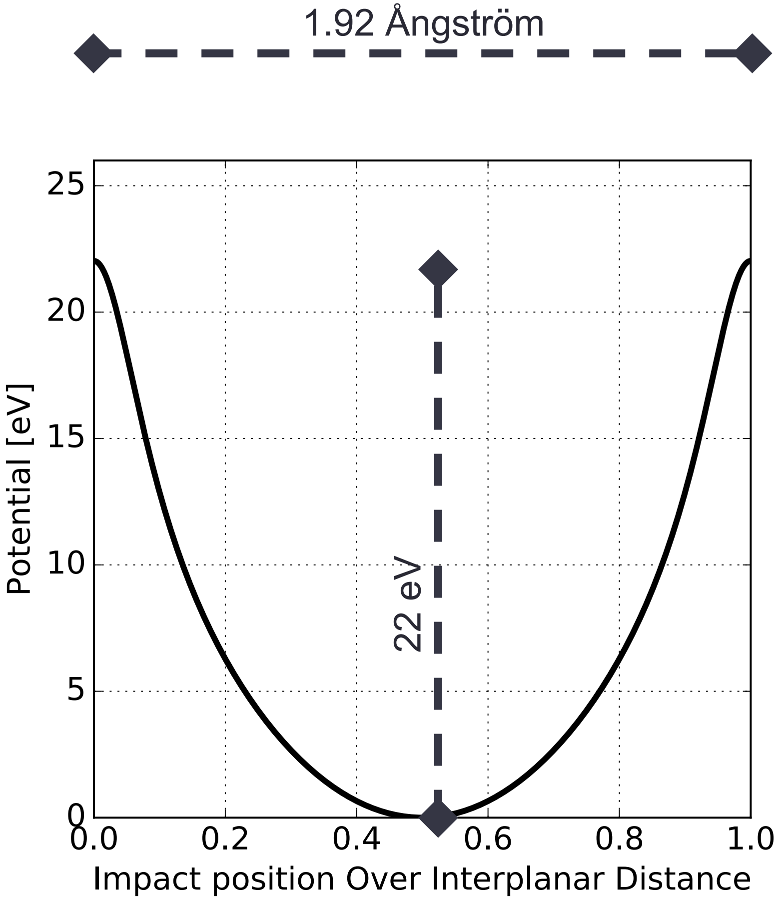
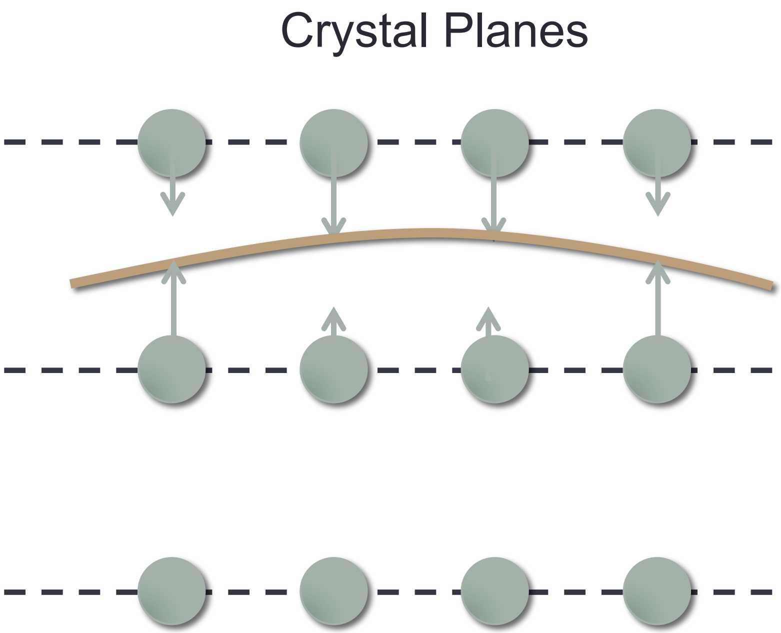
Inter-planar potential for Si (110)



ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)

Charged Particle-Crystal Interaction



- Particles which impact the crystal parallel to a crystallographic plane are forced by the strong electromagnetic field to bounce between the atomic planes, i.e. to channel.

- Channeling occurs when the angle between the particle trajectory and the crystallographic plane (θ) is lower than the so-called *channeling critical angle* (θ_c).

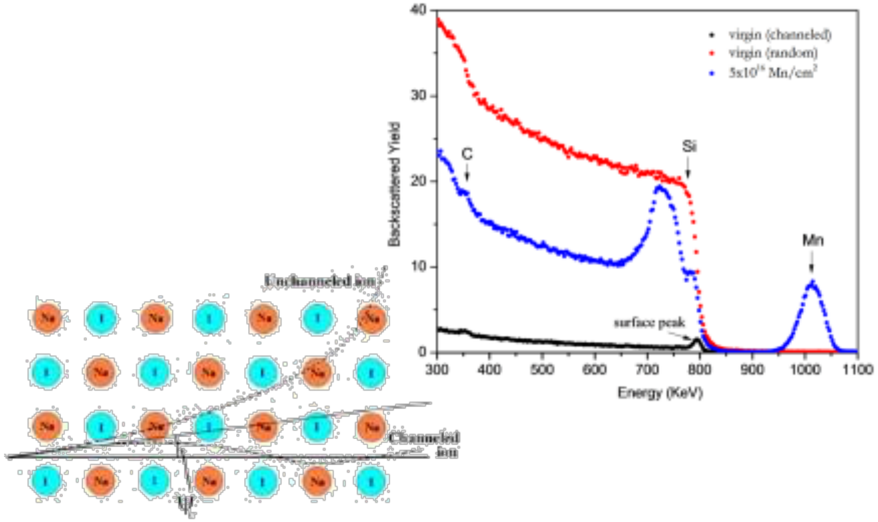
- The angle θ_c is proportional to the square root of the well depth of the inter-planar potential divided by the particle energy.

$$|\theta| < \theta_c = \sqrt{2U/E}$$

Channeling Applications

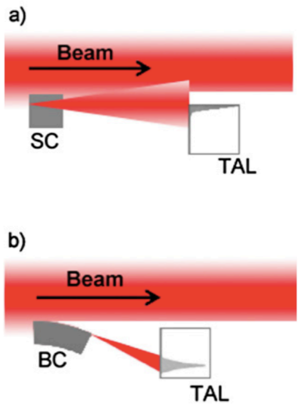
RBS-Channeling Material analysis

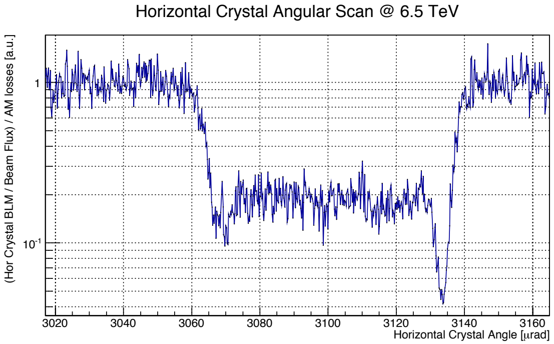
- Rutherford Back-Scattering Channeling allows to discover the presence and the quantity of dopant in semiconductor and to determine the presence of defects in the crystal surface



Beam loss reduction in accelerators

- Oriented ordered structure can modify particle trajectories inside a medium leading to a sensible variation of the interaction rate with atomic nuclei.
- Measurement in the CERN LHC ring with 6.5 TeV/c protons and Si (110) crystal varying the crystal orientation with respect to beam direction showed a of the ratio of the beam loss.





Nuclear interaction probability under channeling

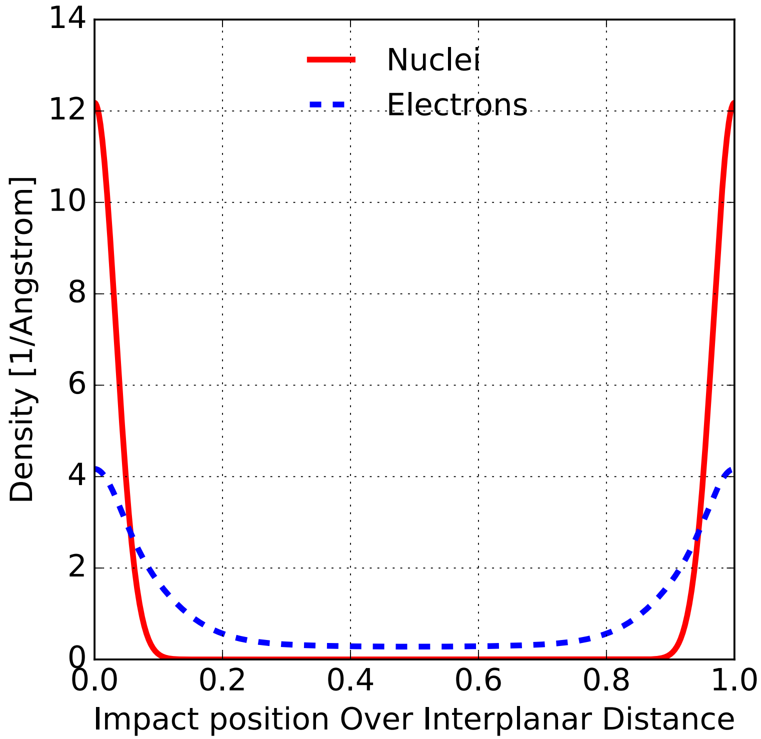
Nuclear interactions under channeling

Channeling

- Under channeling the probability of inelastic nuclear interaction (η) is not the same for all the incoming particles.
- Indeed, the density of nuclei and electrons varies as a function of the particle position in the crystal channel.
- We define the nuclei density ratio (ξ) as the ratio of the density experienced by a particle under channeling (ρ) over the density experienced by a particle interacting with an amorphous material (ρ_{am}).

$$\xi = \rho / \rho_{am}$$

Inter-planar electrons and nuclei density for Si (110)



d_p = interplanar distance = 1.92 Angstrom

Nuclear interactions under channeling

Geant4

- In order to quantify the nuclei density ratio under channeling we used Geant4[1,2].
- Geant4 is a toolkit for the simulation of the passage of particles through matter.
- Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.
- Examples of application are the simulation of the response of the ATLAS and CMS detectors at the CERN-LHC or the prediction of the distribution of dose deposited in the tissue irradiated during ion therapies.

Channeling simulations

- We run Geant4 simulation[1,2] of channeled particles for a 400 GeV/c collimated proton beam impinging on a (110) Silicon crystal. For such beam the critical angle for channeling is:

$$\theta_c = 10 \mu rad$$

- The Geant4 simulation allows taking into account single incoherent scattering, nuclear interactions, energy loss. A specific extension of Geant4 for channeling was used[3].
- With the usage of Geant4 they are possible the tracking the particle trajectory into the crystal structure and the modification of the cross section as a function of the nuclei density ratio.

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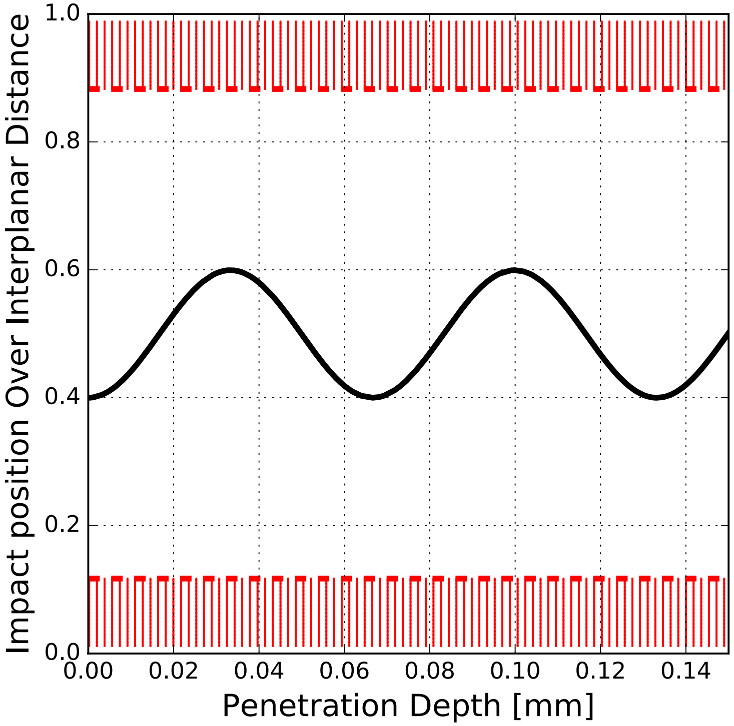
[1] S. Agostinelli et al., NIMA, 506, 250 (2003)

[2] J. Allison et al., NIMA 835, 186 (2016)

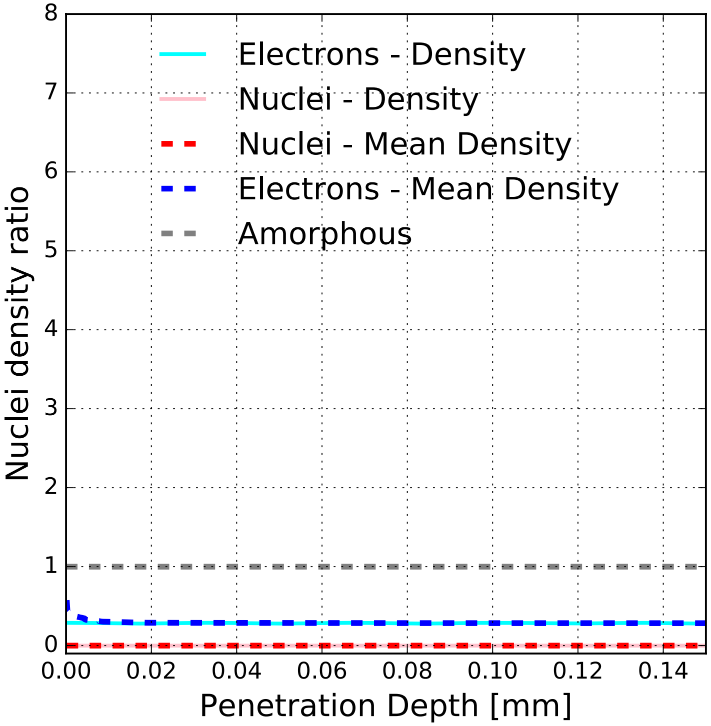
[3] E. Bagli et al., Eur. Phys. J. C 74, 2996 (2014)

Parallel Beam

Trajectory



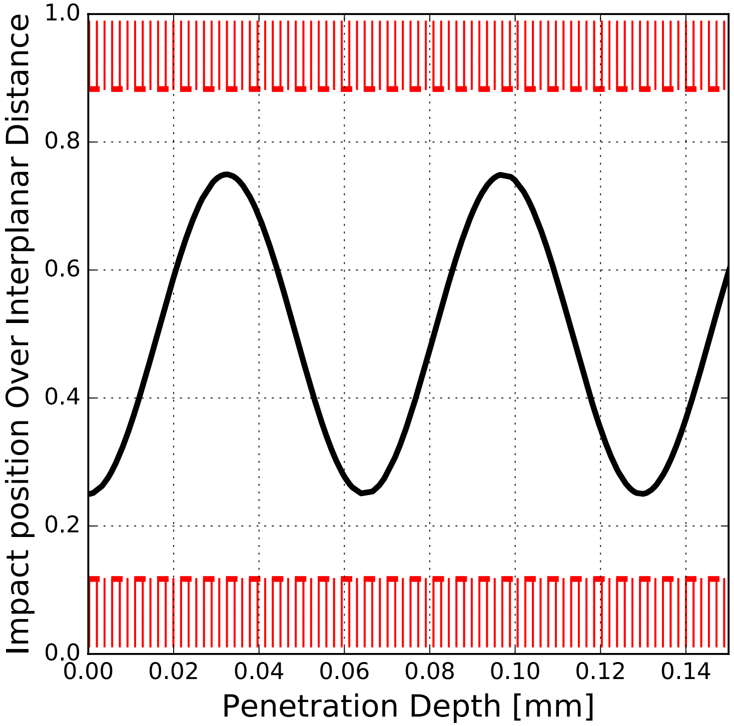
Nuclei density ratio (ξ)



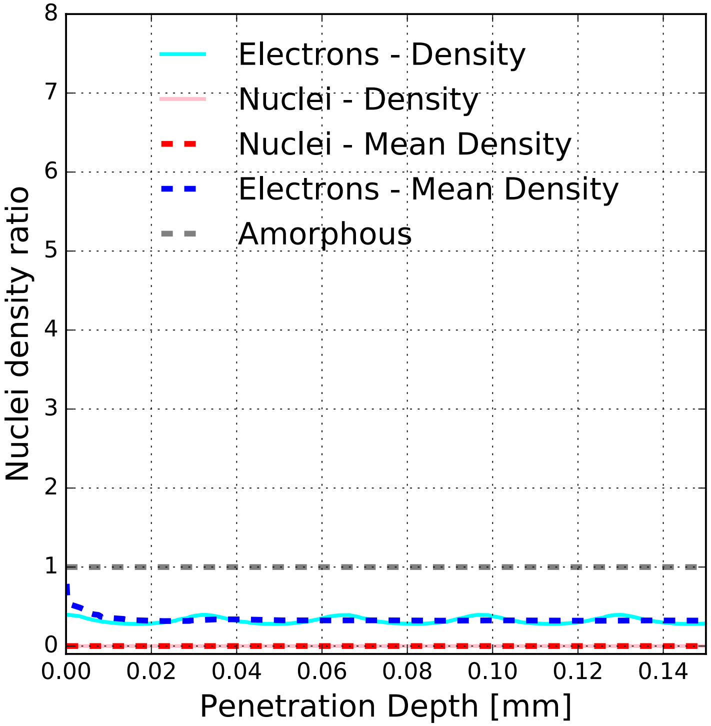
Initial Condition: $[x/d_p = 0.40; \theta/\theta_c = 0]$ d_p = interplanar distance = 1.92 Angstrom

Parallel Beam

Trajectory



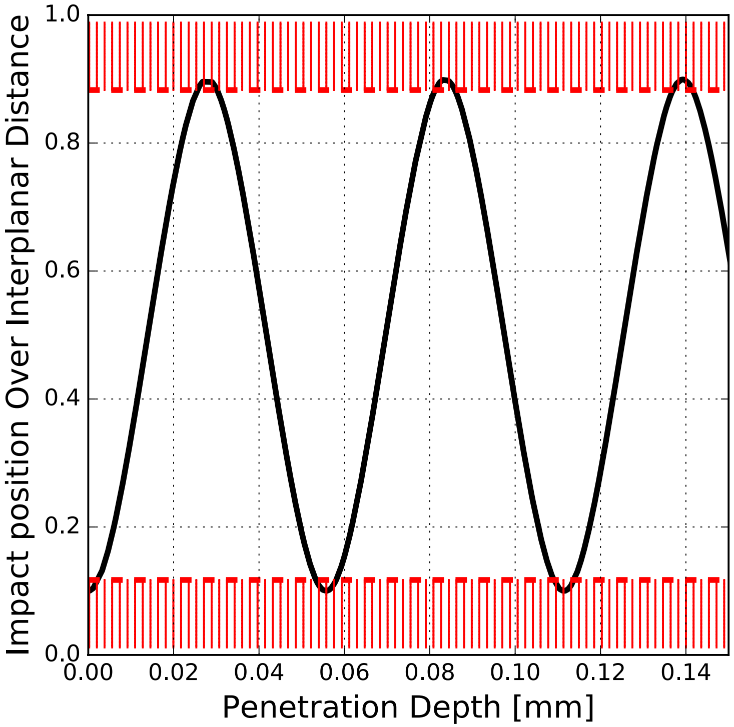
Nuclei density ratio (ξ)



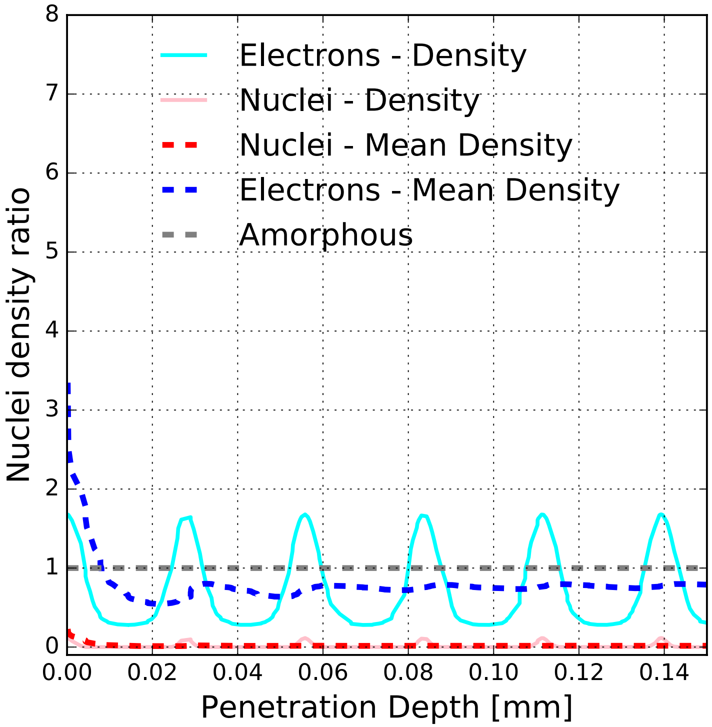
Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 0]$ d_p = interplanar distance = 1.92 Angstrom

Parallel Beam

Trajectory



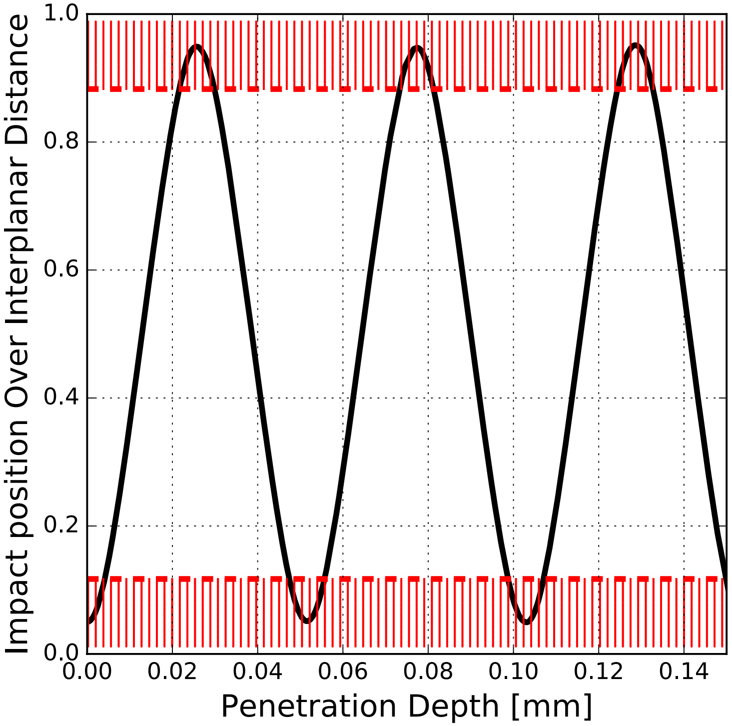
Nuclei density ratio (ξ)



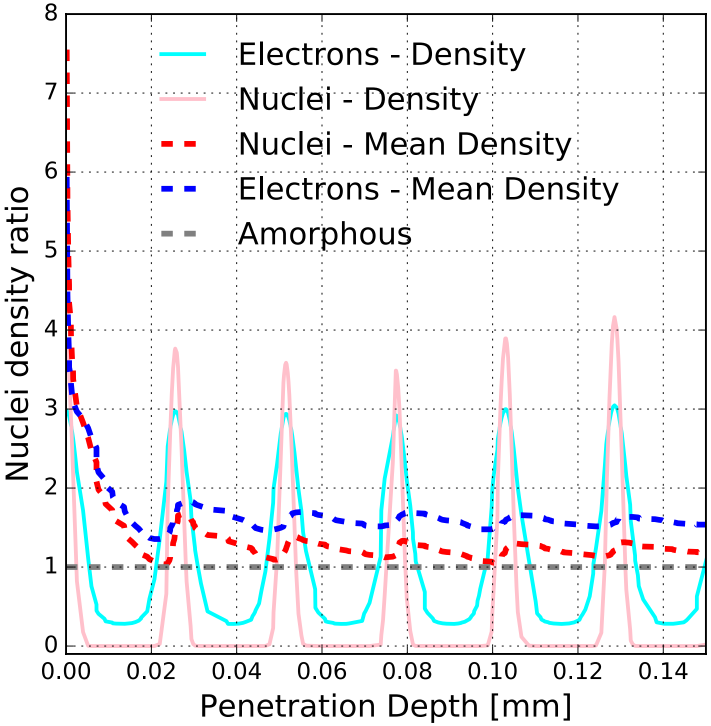
Initial Condition: $[x/d\downarrow p = 0.10; \theta/\theta\downarrow c = 0]$ $d\downarrow p$ = interplanar distance = 1.92 Angstrom

Parallel Beam

Trajectory



Nuclei density ratio (ξ)



Initial Condition: $[x/d_p = 0.05; \theta/\theta_c = 0]$ d_p = interplanar distance = 1.92 Angstrom

Nuclear interactions under channeling

Real case

- With standard accelerators it is impossible to select the impact position of a particle on the crystal channel with a sub-nm precision.
- As a consequence, we need to change the impact angle with respect to the crystal planes in order to observe a similar modification of the nuclei density ratio.

Simulation

- In this second simulation we deliberately choose as initial condition for impact position:

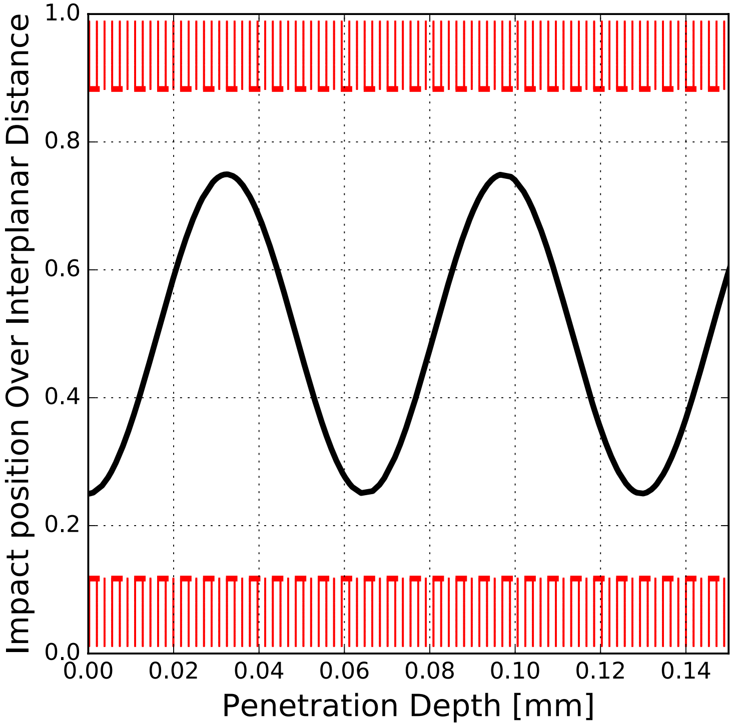
$$x/d_p = 0.25$$

- The incoming angle is chosen as a fraction of the critical angle:

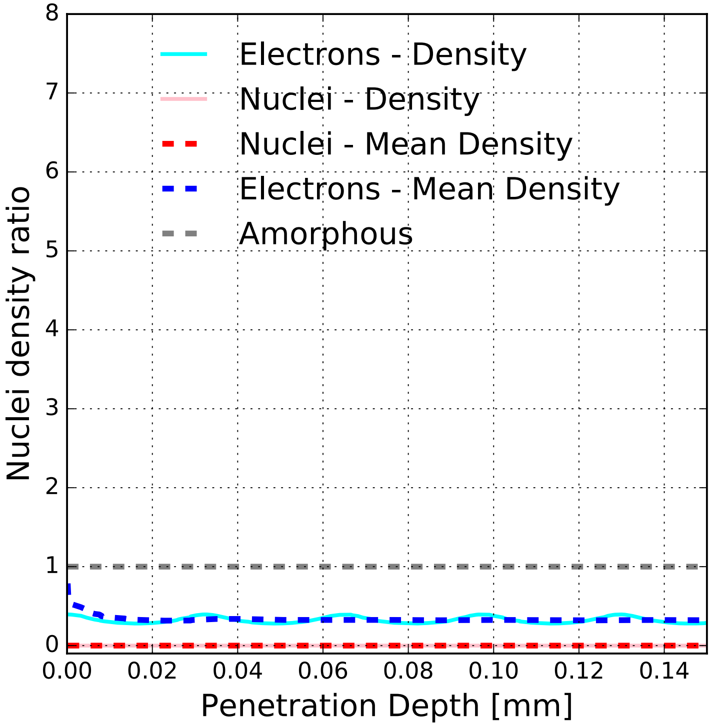
$$\theta/\theta_c$$

Misaligned Beam

Trajectory



Nuclei density ratio (ξ)

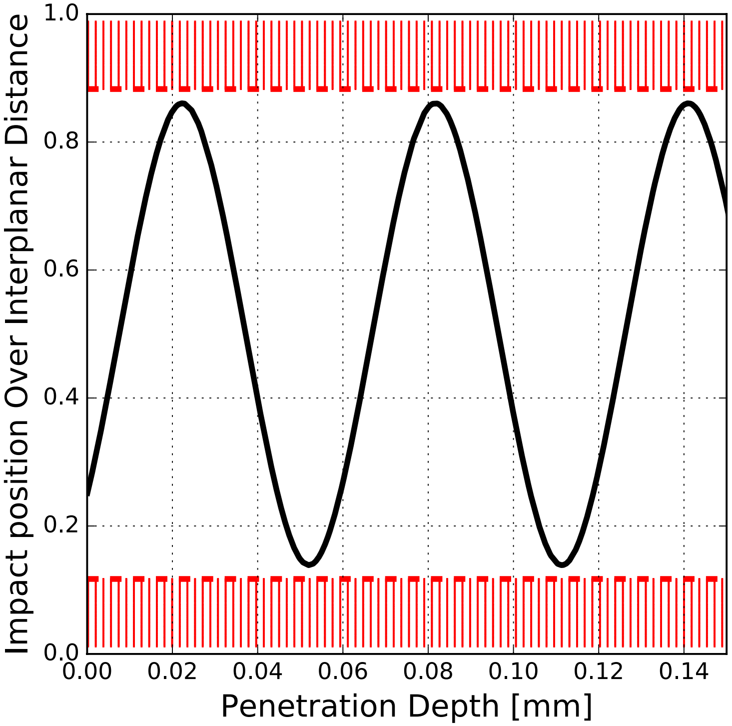


Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 0.0]$

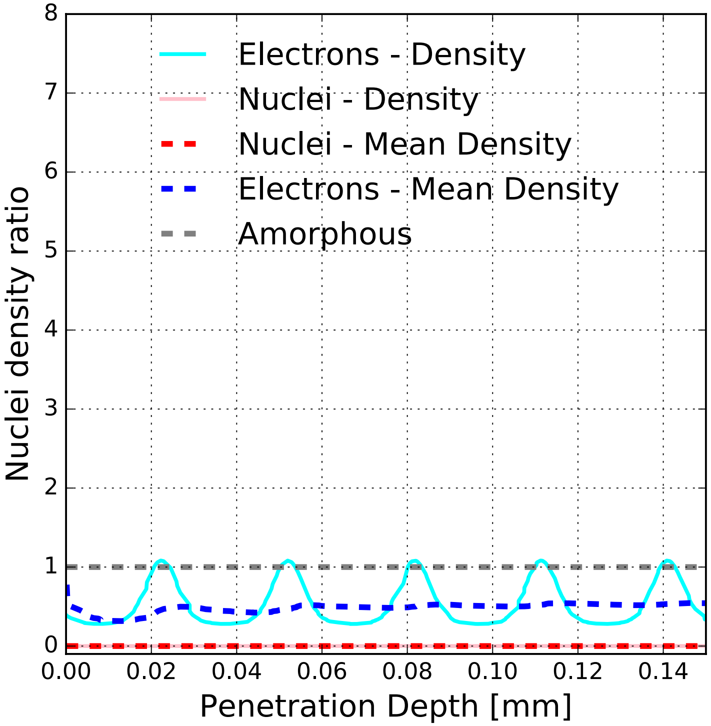
d_p = interplanar distance = 1.92 Angstrom

Misaligned Beam

Trajectory



Nuclei density ratio (ξ)

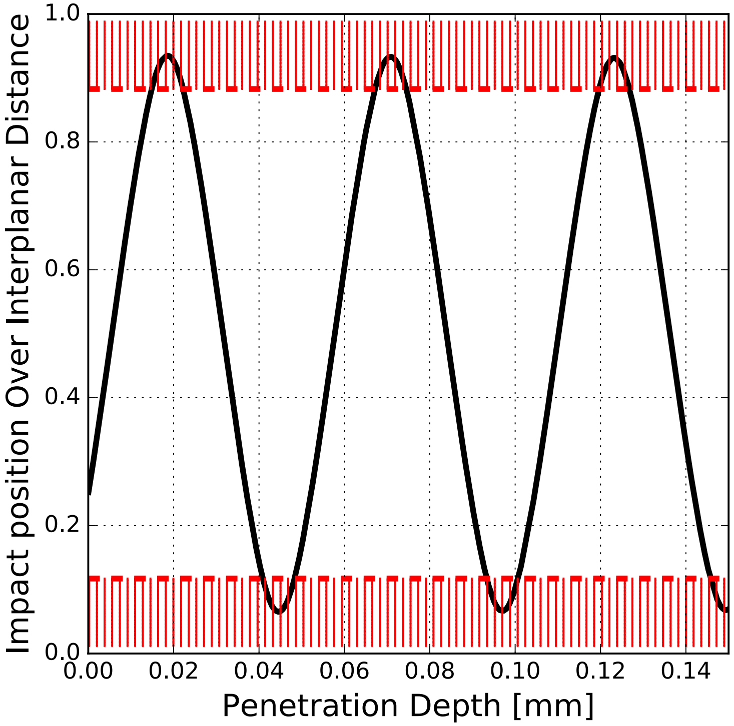


Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 0.5]$

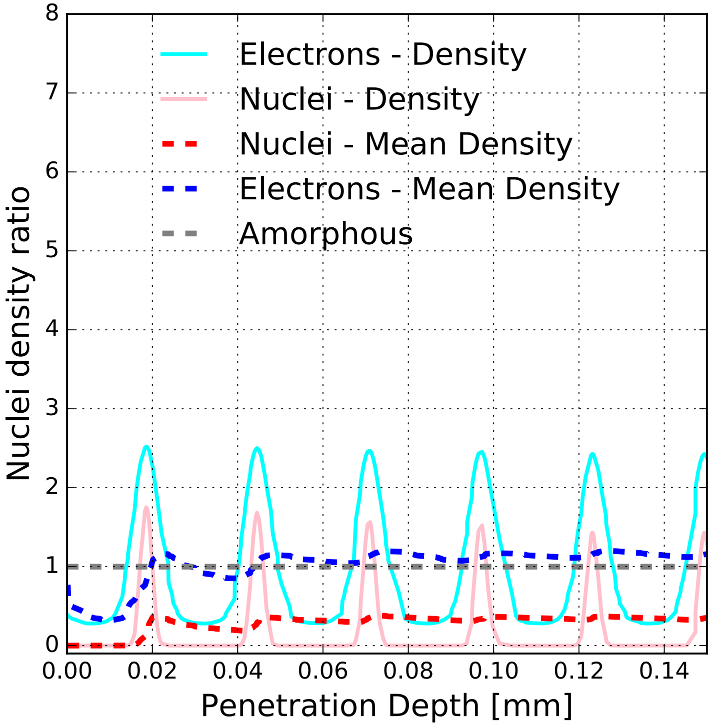
d_p = interplanar distance = 1.92 Angstrom

Misaligned Beam

Trajectory



Nuclei density ratio (ξ)

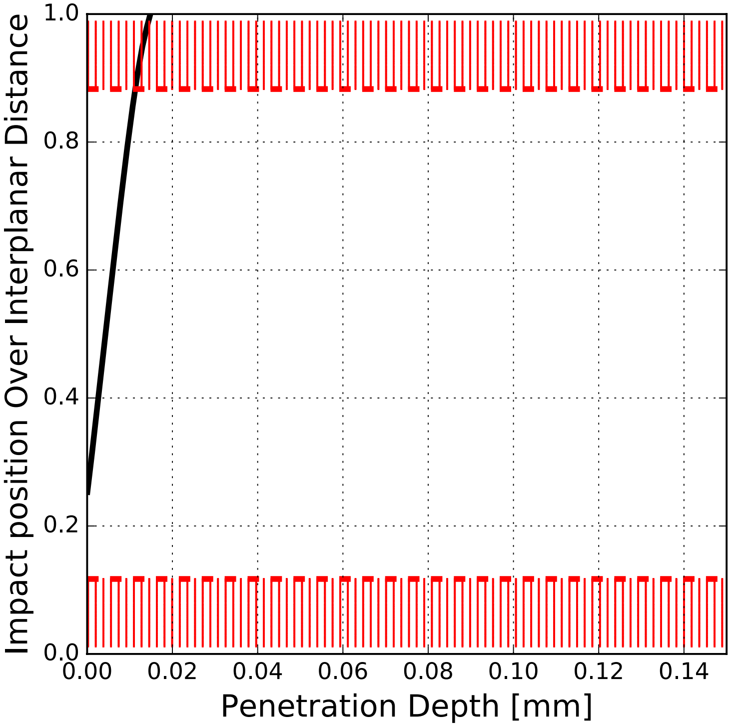


Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 0.75]$

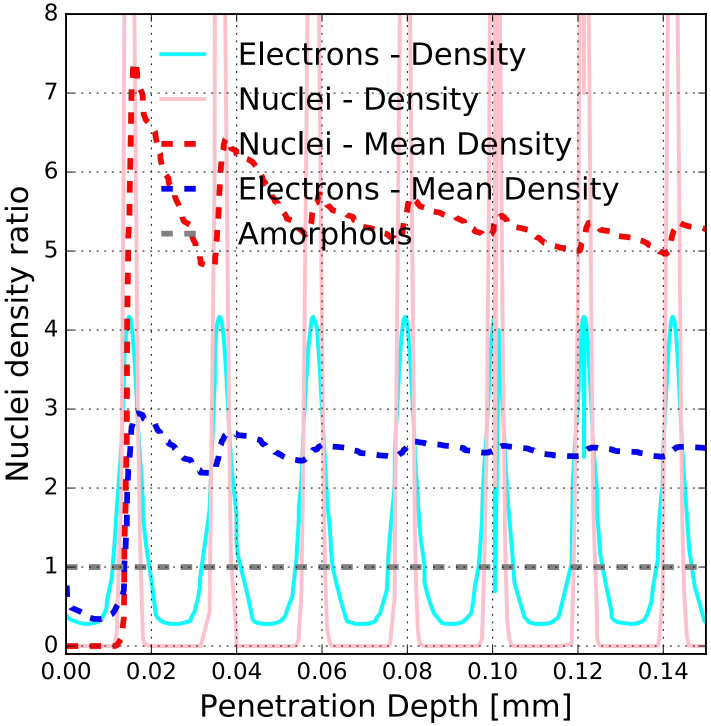
d_p = interplanar distance = 1.92 Angstrom

Misaligned Beam

Trajectory



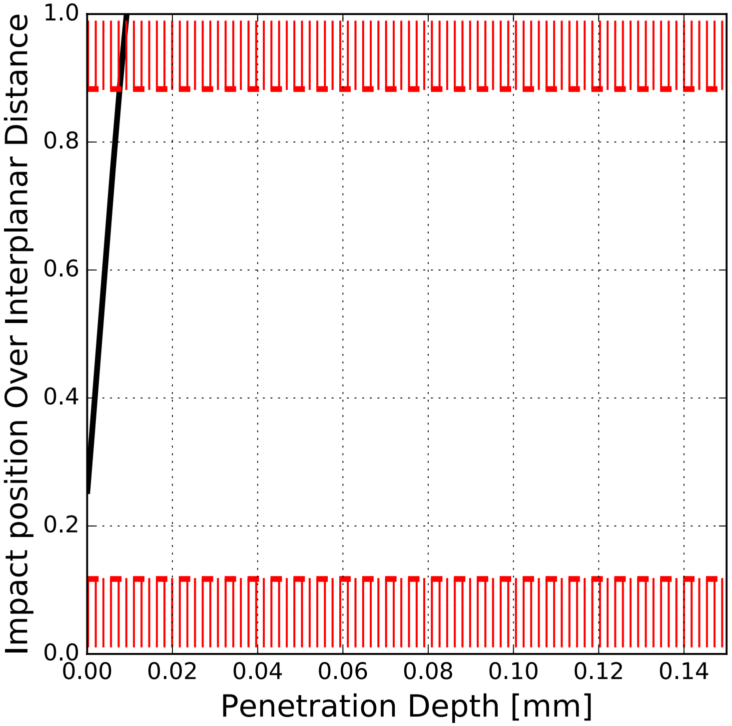
Nuclei density ratio (ξ)



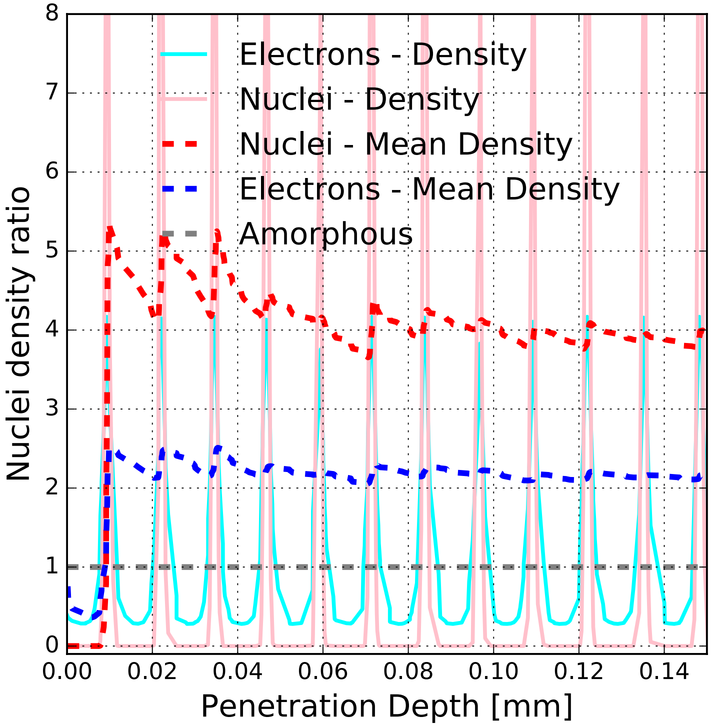
Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 1.0]$ d_p = interplanar distance = 1.92 Angstrom

Misaligned Beam

Trajectory



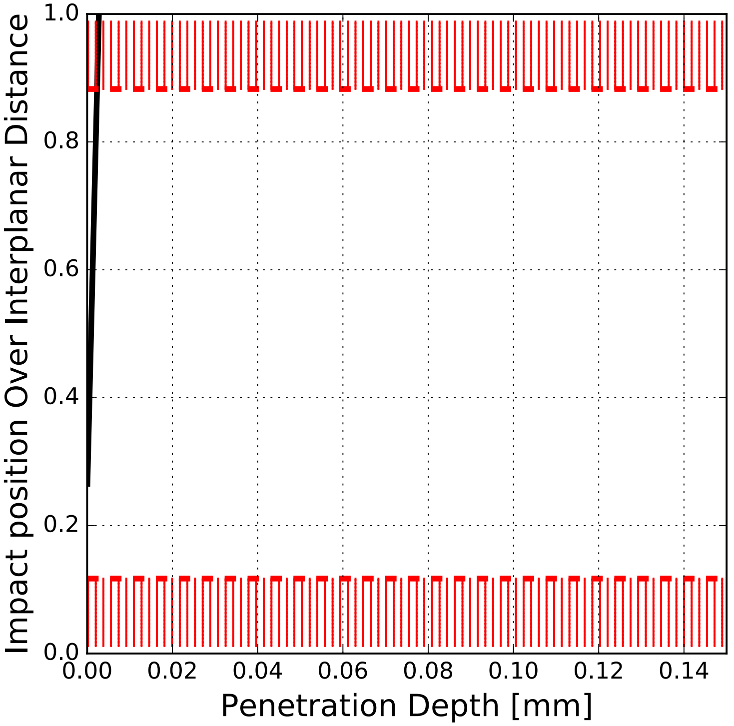
Nuclei density ratio (ξ)



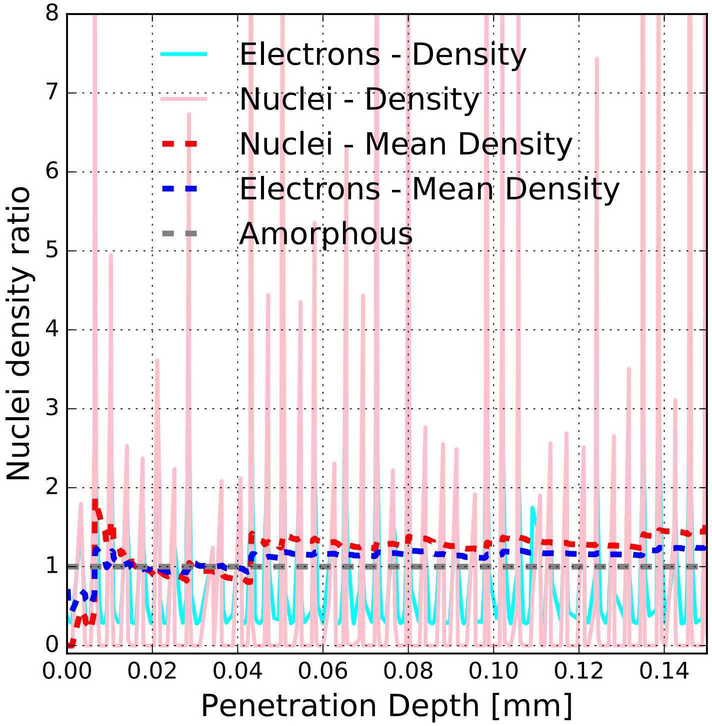
Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 1.5]$ d_p = interplanar distance = 1.92 Angstrom

Misaligned Beam

Trajectory



Nuclei density ratio (ξ)



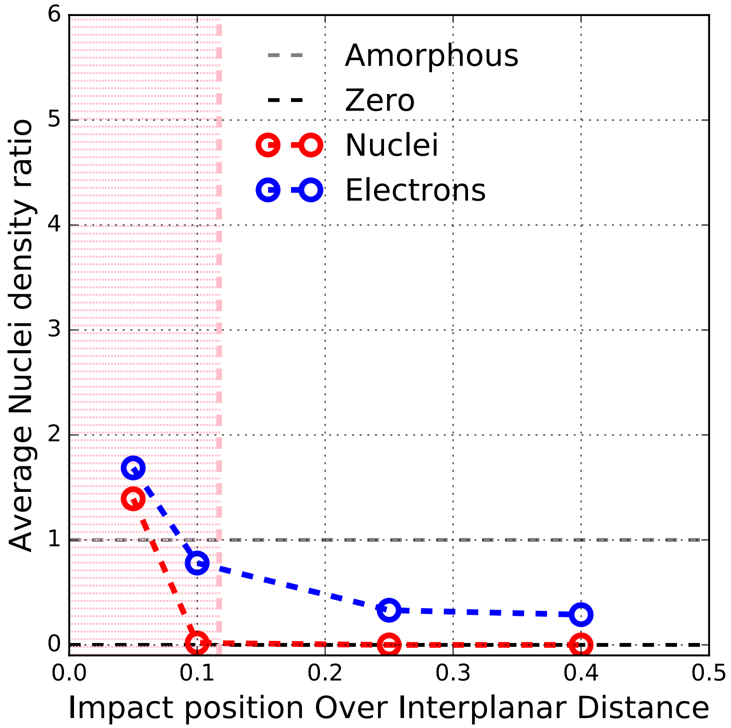
Initial Condition: $[x/d_p = 0.25; \theta/\theta_c = 5.0]$

d_p = interplanar distance = 1.92 Angstrom

Nuclear interactions under channeling

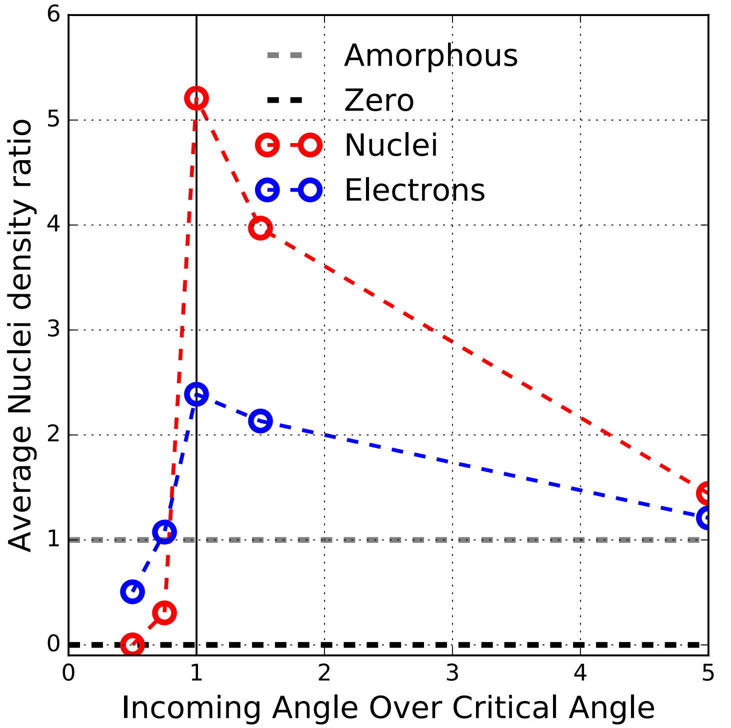
Position

$\theta/\theta\downarrow c = 0$



Angle

$x/d\downarrow p = 0.25$



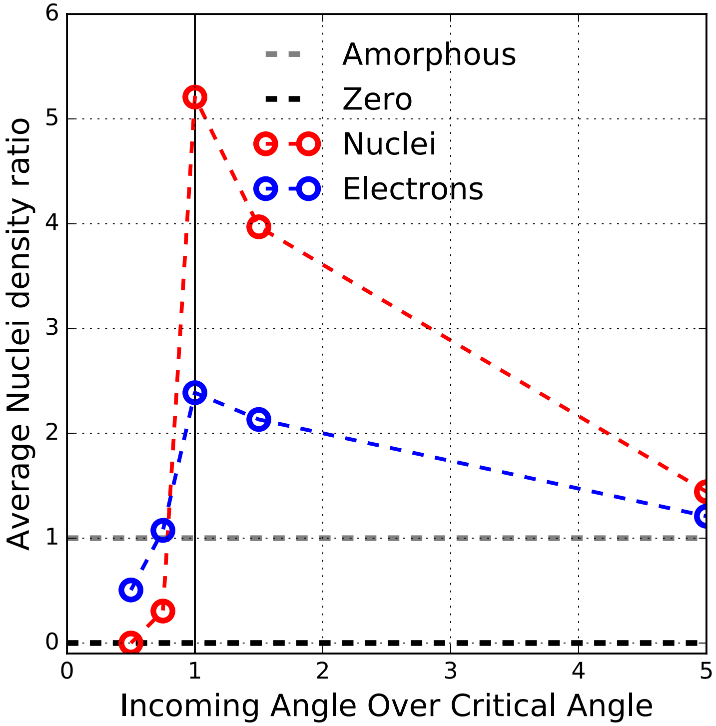
Nuclear interactions under channeling

Starting from the simulations performed, we can define three main regimes:

- $|\theta| \ll \theta_c \qquad \eta \longrightarrow 0$
- $|\theta| \sim \theta_c$
  $\eta > 1$
- $|\theta| \gg \theta_c \qquad \eta \longrightarrow 1$

Angle

$x/d_p = 0.25$

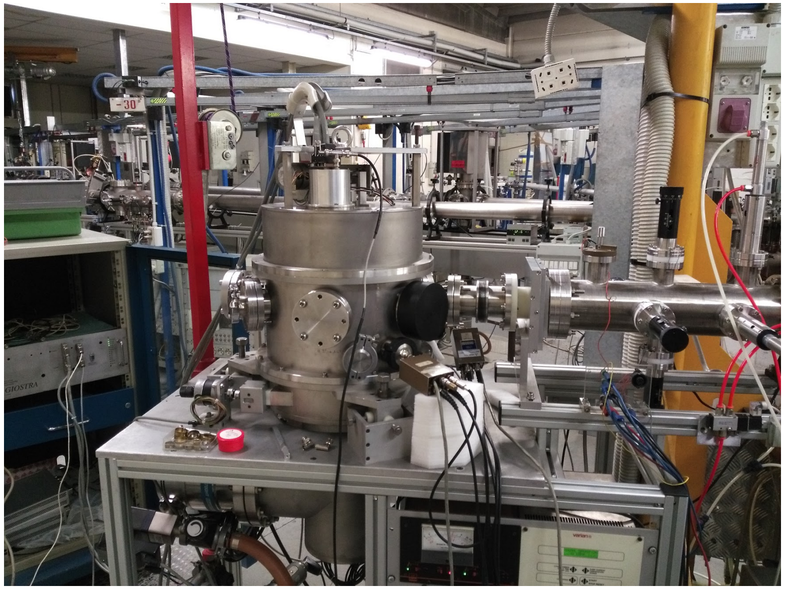


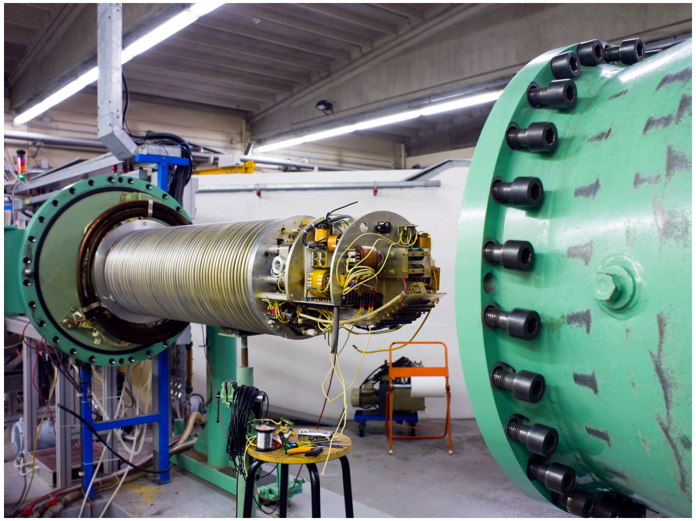
Experiment at INFN Legnaro Laboratories

AN2000 accelerator

AN2000 at INFN-LNL

- AN2000 is an electrostatic-type accelerator with a maximum voltage terminal of 2 MV.



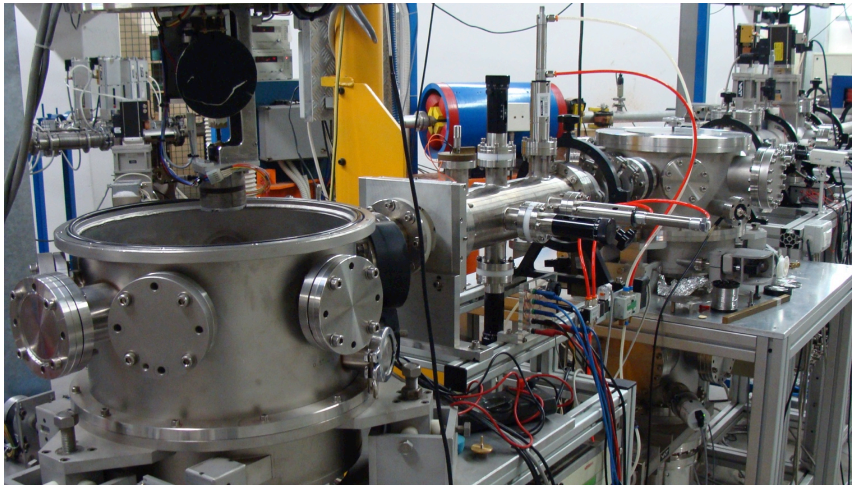


- The limited output energy available by such a compact-size accelerator makes it an ideal facility to promote nuclear reaction events with the first layers of target materials.

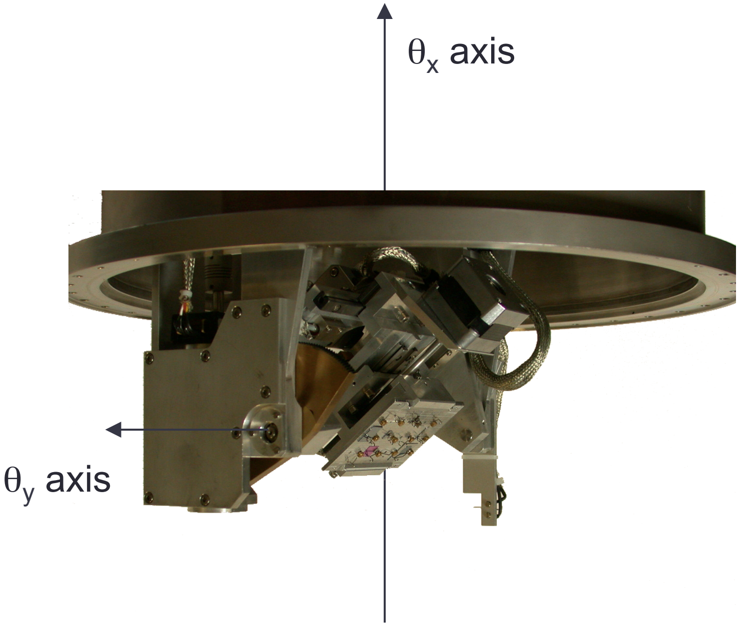
RBS-Channeling at AN2000

At the RBS-Channeling line of AN2000 a high resolution goniometer is present:

- Angular Resolution 0.01°
- Minimum pressure ≈10^{-7} mbar



0.01° ≈ 0.2 *mrad*



The goniometers allows to align the crystal plane (θ_x axis) and the crystal axes (θ_y axis) with respect to the incoming beam within the critical channeling angle.

$$\theta_c(2MeV)=0.19^\circ$$

RBS-Channeling at AN2000

- Two Silicon detectors are mounted in the chamber, one for the RBS and one for the nuclear resonance analysis (NRA), to allows for the simultaneous measurement of the two quantities.

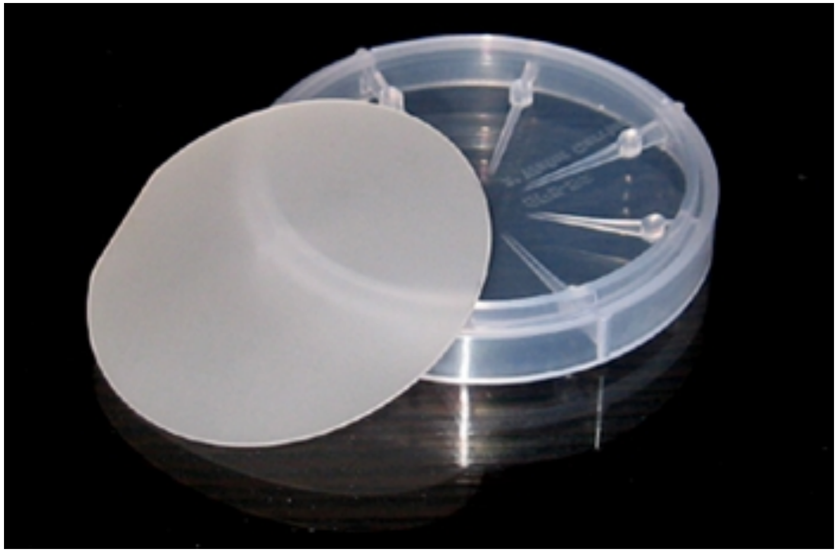
	S (mm^2)	d (mm)	Ang (deg)
NRA	300	40	150
RBS	25	110	160

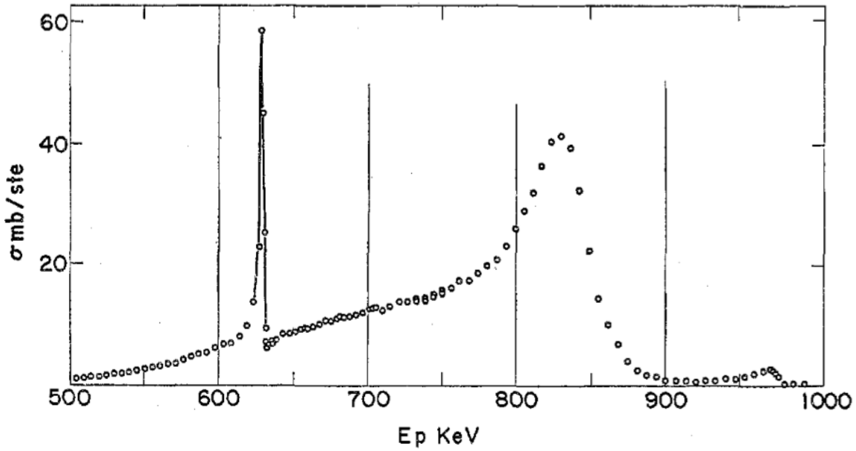
Al_2O_3 crystal

We decided to use a nuclear reaction with a resonance at energy accessible by the AN2000 accelerator. The chosen reaction is the

$$^{18}O\ (p,\alpha)\ ^{15}N$$

reaction at ~627 KeV[1] with a Q-value of ~4.0 MeV.





- We choose the Al_2O_3 aluminum oxide C-plane wafer for the experiment, i.e. the <0001> direction, that has an hexagonal crystal structure.

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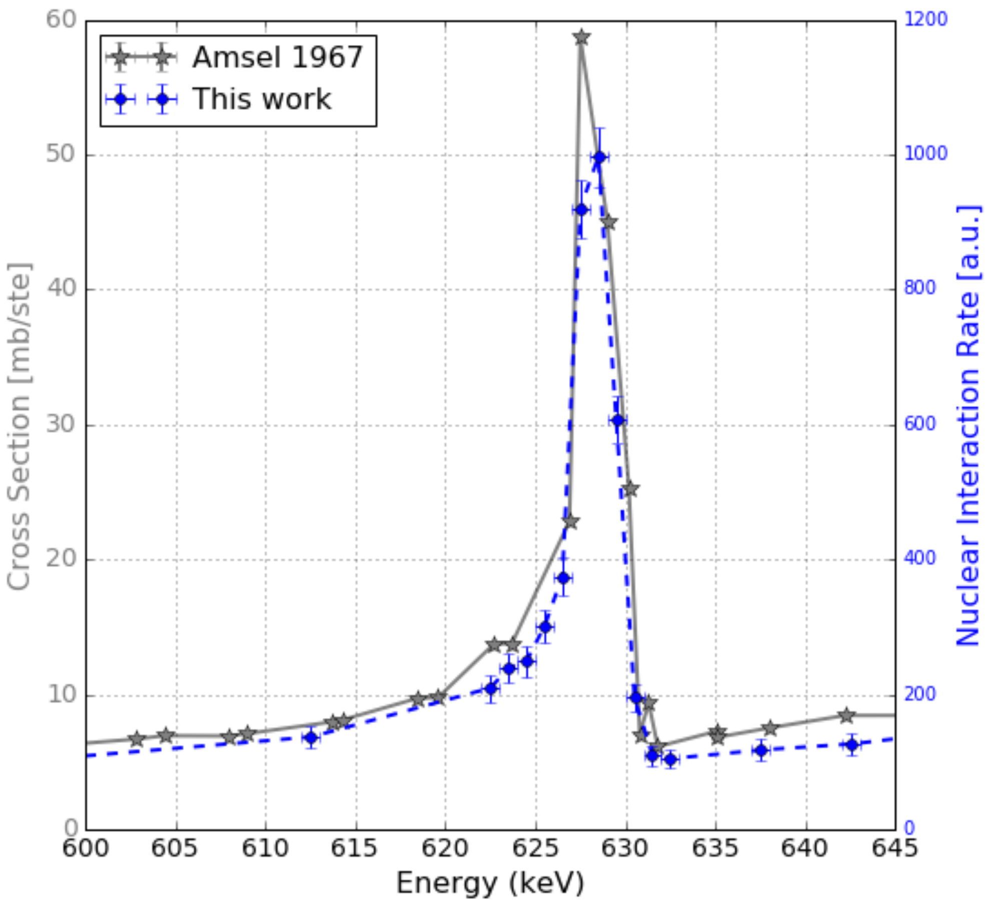
[1] G. Amsel, D. Samuel, Analytical Chemistry 39, 1689 (1967)

^{18}O (p,α) ^{15}N

- A sputtered thin-layer of 95% ^{18}O on a Si wafer was used to redone the experimental measurement of the ^{18}O (p,α) ^{15}N cross-section.
- At the end, the beam energy was set to 642.5 keV, in order to let the nuclear resonance occurs inside the crystal bulk.



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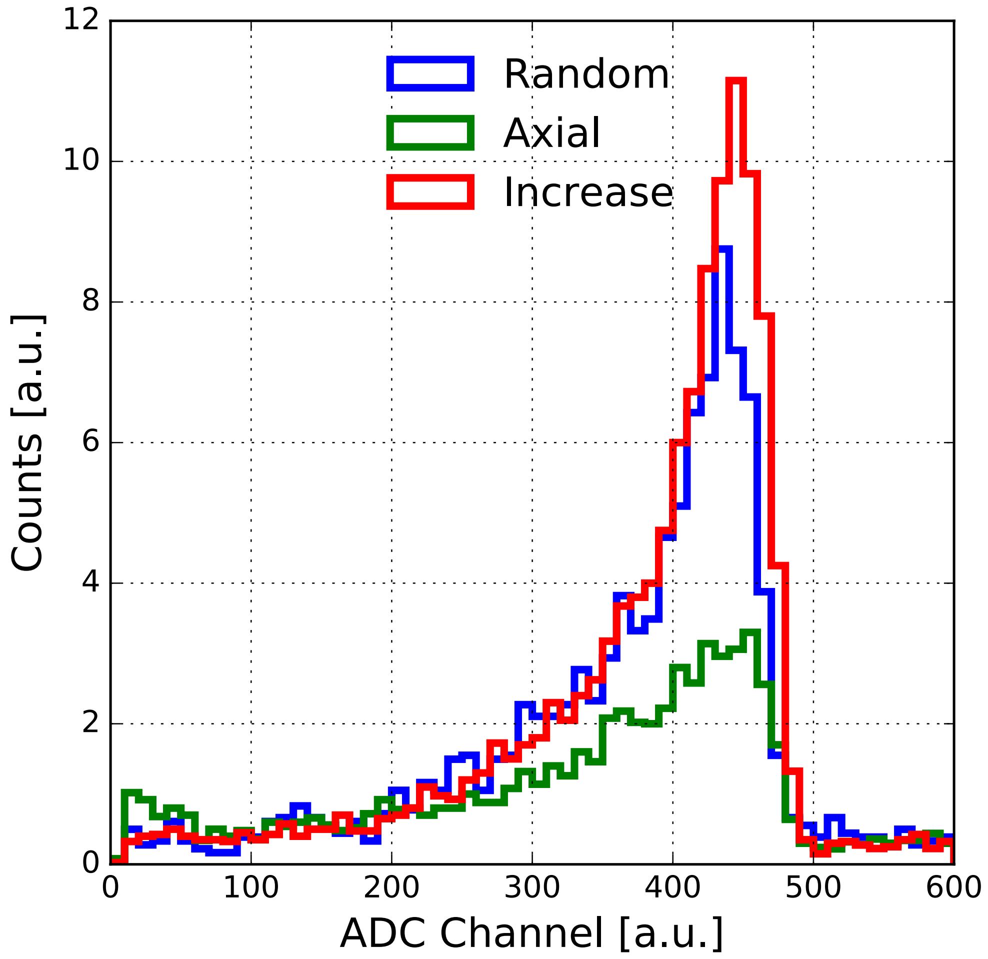
[1] G. Amsel, D. Samuel, Analytical Chemistry 39, 1689 (1967)

Al_2O_3 crystal - NRA

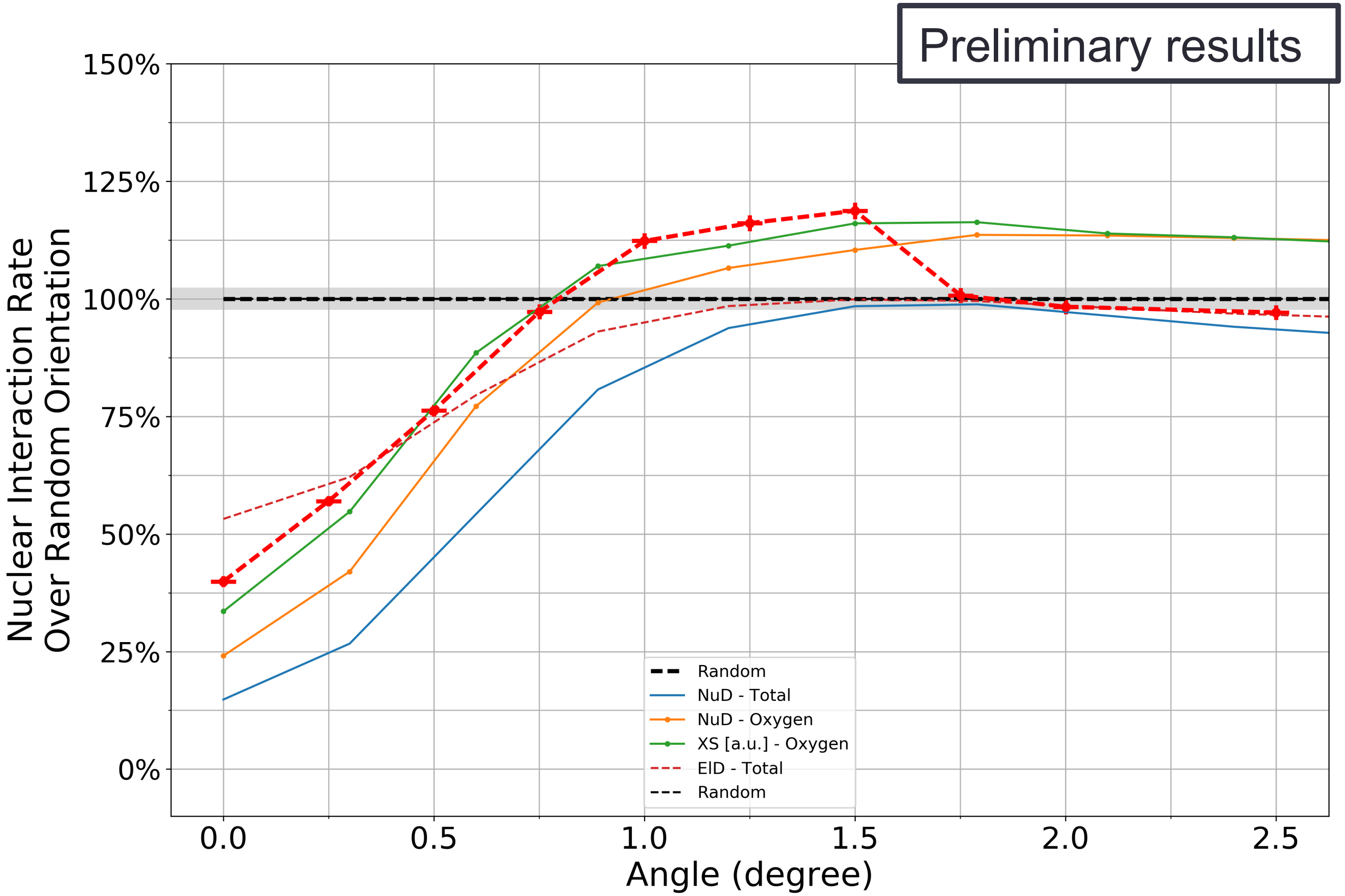


- With Al_2O_3 crystal aligned parallel to the <0001> axis, the counts are lowered.

- For a misalignment angle comparable to the critical angle for channeling of the Al_2O_3 <0001> axis

$$\theta_c (645 keV) \sim 1.25^{\circ}$$

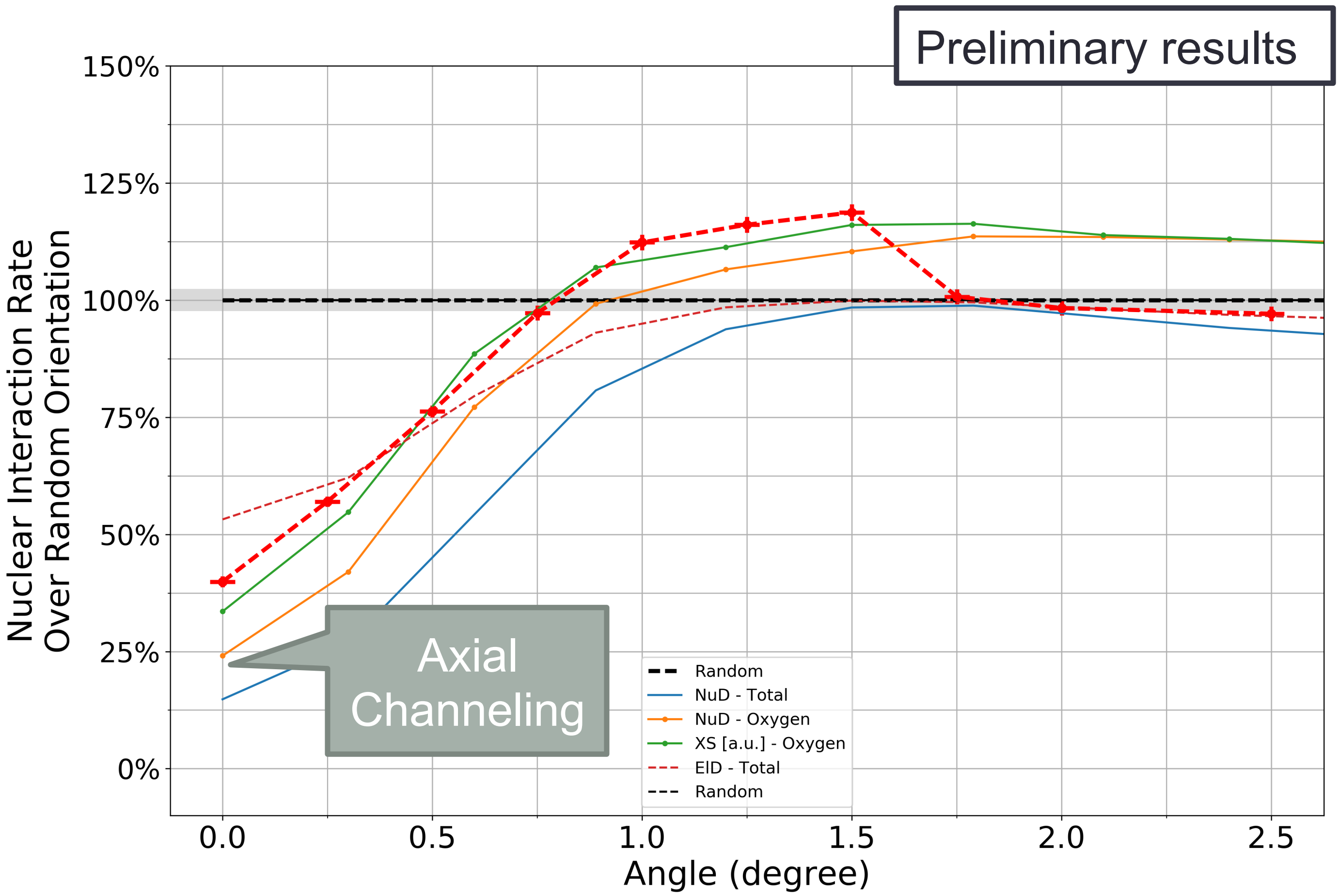
Al_2O_3 crystal - NRA



Al_2O_3 substrates, <0001> axis, $^{18}O(p,\alpha)\,^{15}N$ reaction

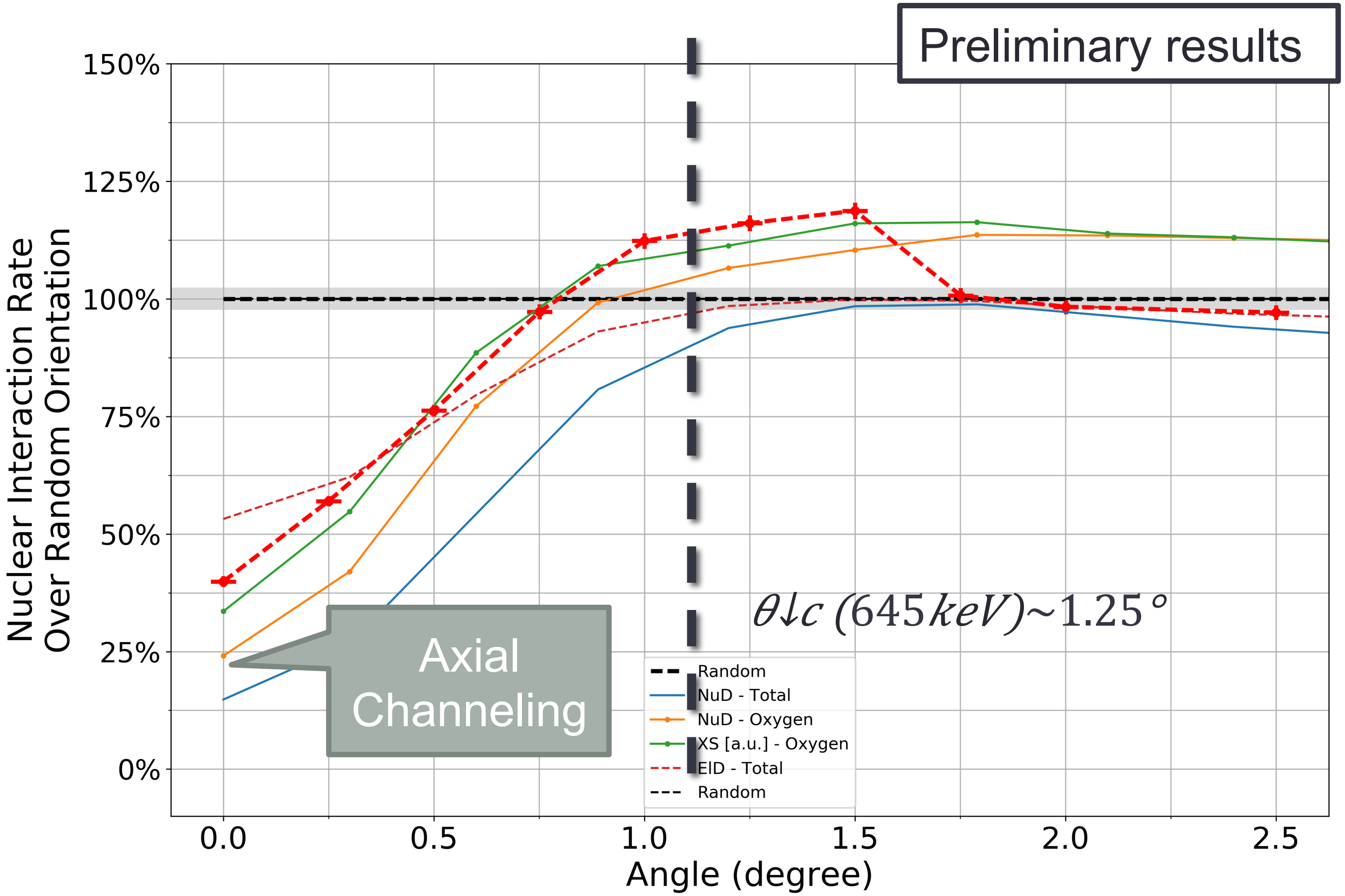
Al_2O_3 crystal - NRA

Preliminary results



Al_2O_3 substrates, <0001> axis, $^{18}O(p,\alpha)\,^{15}N$ reaction

Al_2O_3 crystal - NRA



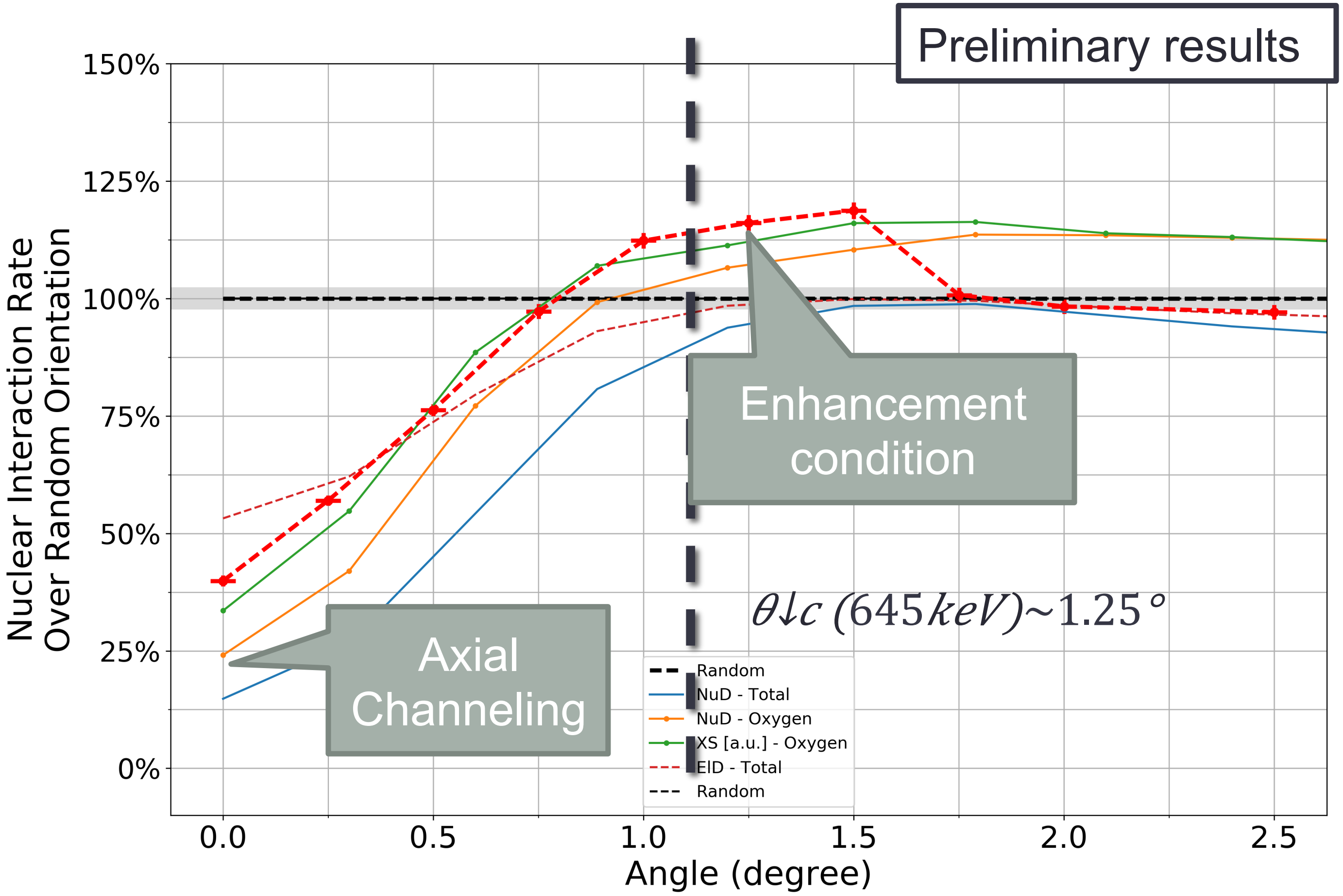
Preliminary results

$\theta\downarrow c\ (645 keV) \sim 1.25°$

Axial Channeling

Al_2O_3 substrates, <0001> axis, $^{18}O(p,\alpha)\ ^{15}N$ reaction

Al_2O_3 crystal - NRA



Preliminary results

Enhancement condition

Axial Channeling

$\theta_c (645 keV) \sim 1.25^\circ$

Al_2O_3 substrates, <0001> axis, $^{18}O(p,\alpha)\ ^{15}N$ reaction

Summary and conclusions

- Microscopically ordered structures prevent the trajectories of charged particles to follow random directions, causing the variation of the particle interaction rate with nuclei.

- Monte Carlo simulations show that when a particle beam enters a crystal misaligned of one critical angle with respect to a plane, the nuclear encounter probability increases.

- Such enhancement was observed at the AN2000-LNL accelerator with a 642.5 keV proton beam impinging on a Al_2O_3 crystal oriented parallel to the <0001> axis, exploiting the $^{18}O(p,\alpha)\,^{15}N$ resonance at ~627 keV.

- The achieved result is general and it is valid for all the ordered structure for which channeling is possible, from keV to hundreds of GeV/c energies and more.

THANK YOU FOR YOUR ATTENTION