CRYSTAL SIMULATION CODE AND NEW COHERENT EFFECTS IN BENT CRYSTAL AT THE LHC

The 6th International Conference - Channeling 2014

Charged & Neutral Particles Channeling Phenomena

October 10, 2014 Capri (Naples) Italy

A.I. Sytov, V.V. Tikhomirov

Belarusian State University,

Research Institute for Nuclear Problems

BSU *INP*

Outline

- **CRYSTAL** simulation code for particle tracking in crystal.
- Channeling effect simulation with the CRYSTAL program.
  - Simulation of the H8 experiment at the CERN SPS.
  - Simulation of 7 TeV proton beam deflection at the LHC.
  - New effects for channeling: **dechanneling peaks**, **ionization losses over the amorphous level**.
- Application of the new effects at the LHC.
  - Channeling in a crystal with the **cut**.
  - The multiple volume reflection in one bent crystal (**MVROC**).
  - Combined action of the **MVROC** and **channeling**.
  - Comparison of the efficiency of the new effects for the LHC crystal-based collimation system.

CRYSTAL simulation code*

Main conception – tracking of charged particle trajectories in crystal by solving the equation of motions

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential

Simulation of the next physical processes:

- Multiple and single Coulomb scattering on nuclei and electrons.
- Nuclear scattering (elastic, quasielastic, inelastic)
- Ionization energy losses
- Crystal geometry (entrance/exit through the crystal lateral surface; miscut angle)

Spline interpolation of

- Interplanar (interaxial) potential
- Interplanar (interaxial) electric field
- Nuclear density
- Electron density

Advantages:

- high calculation speed (**up to 2000 particles/s/CPU**)
- algorithm universality

*A.I. Sytov, Vestnik. Belarusian. Univ. Series 1 N2 (2014), 48-52, (in Russian).

Simulation of 400 GeV proton deflection at the SPS (H8 STF45)*

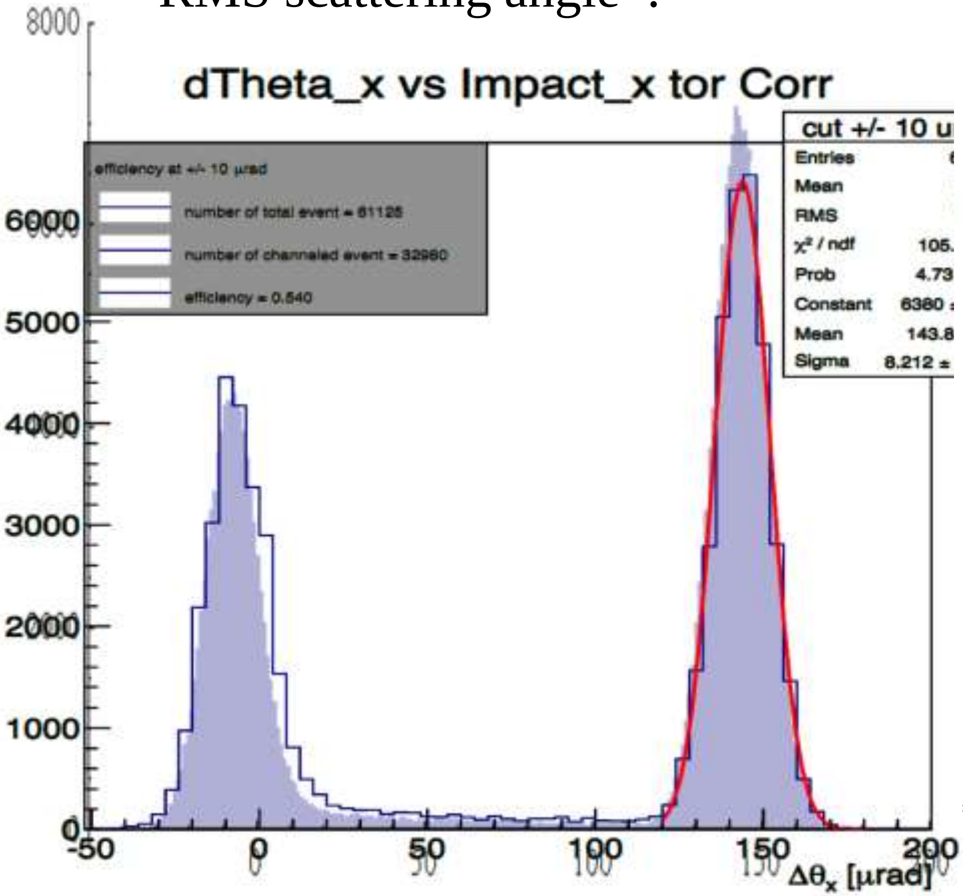
Crystal parameters*

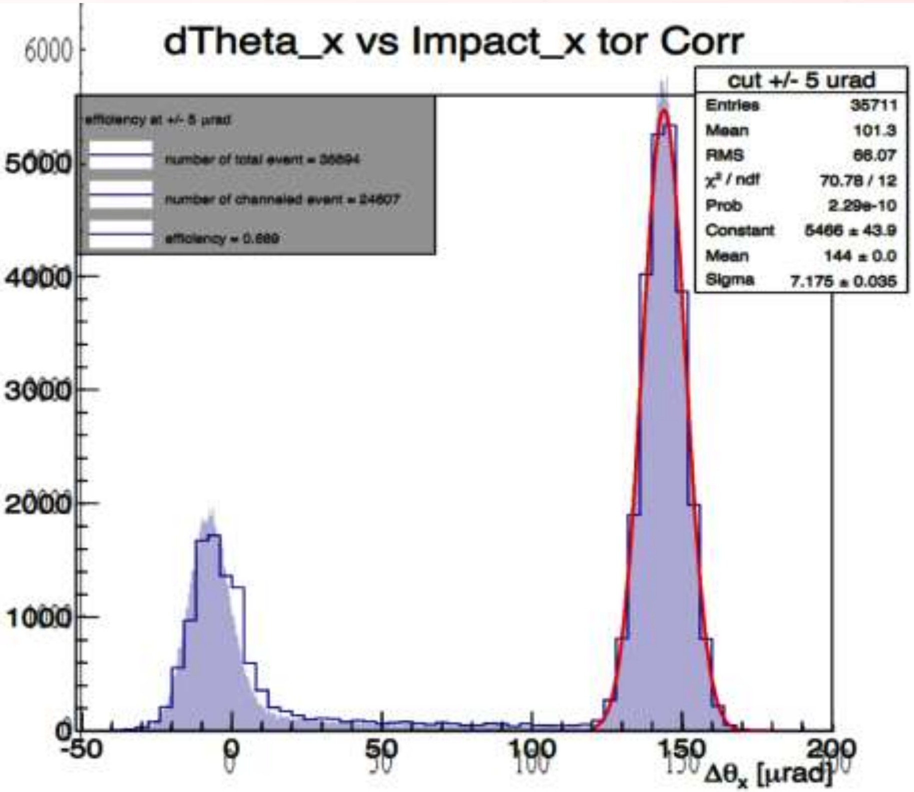
θ_b=143.78 μrad, θ_{tilt}=0 μrad,

Scattering in the H8 beam line*,**

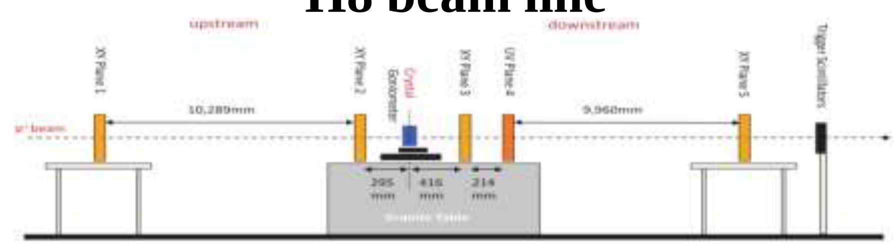
$\theta_{sc.in}$=4.45 μrad, $\theta_{sc.out}$=4.45 μrad,

$\theta_{sc}=\sqrt{\theta_{sc.in}^2+\theta_{sc.out}^2}$=6.29 μrad= RMS scattering angle*.





H8 beam line**



*R. Rossi et al.
H8 Single Pass Test Data Analysis (2014).
**M. Pesaresi et al. JINST 6 (2011) P04006.

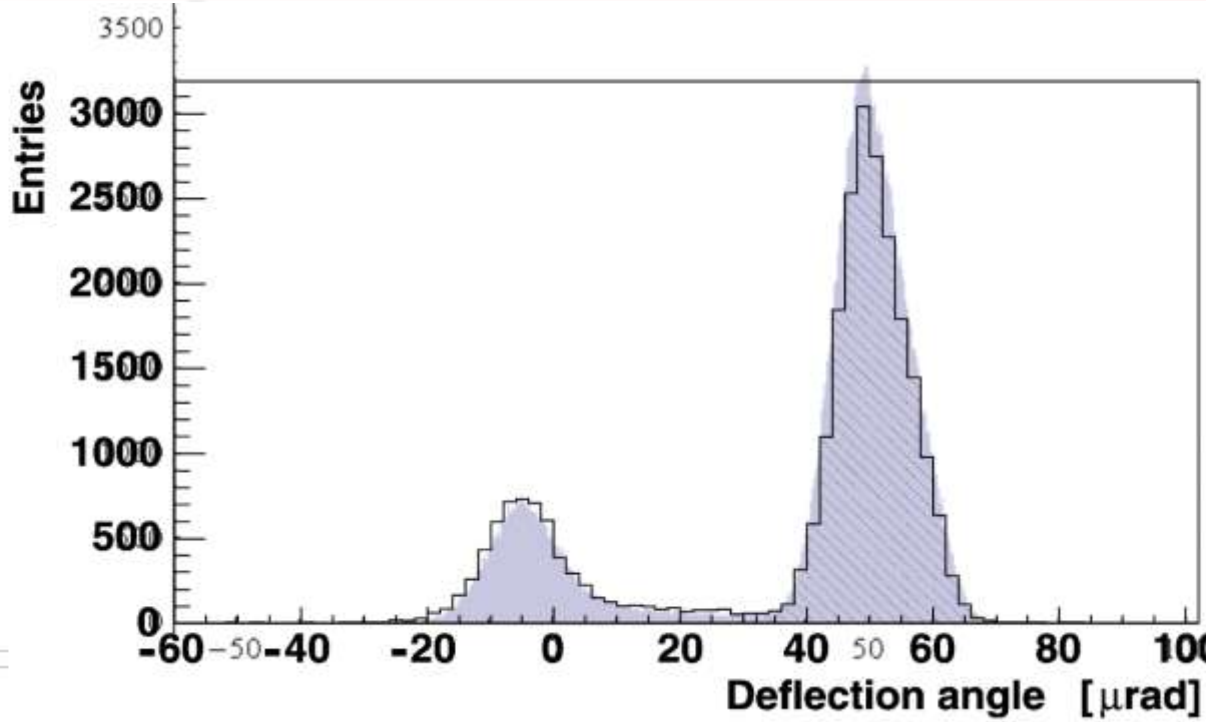
Simulation of 400 GeV proton deflection at the SPS*

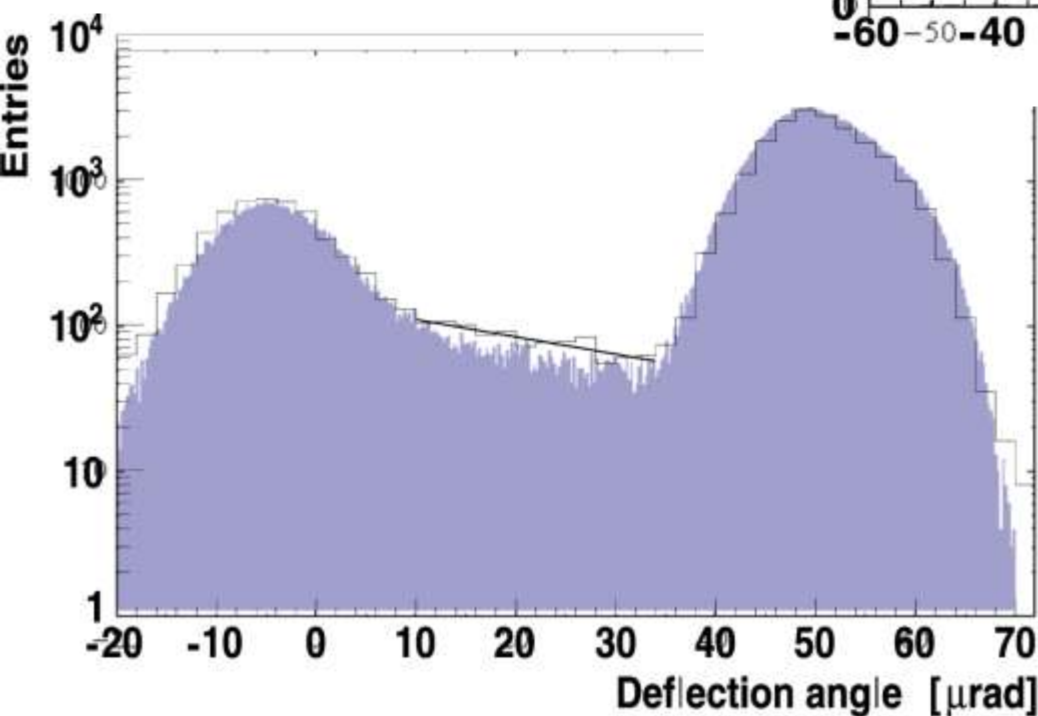
Crystal parameters*

θ_b=48.5 μrad, θ_{tilt}=2.7 μrad,

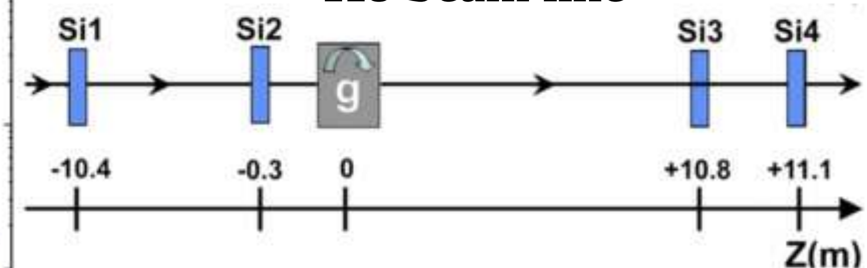
Scattering in the H8 beam line*,**

$\theta_{sc.in}$=2.2 μrad, $\theta_{sc.out}$=2.2 μrad,
$\theta_{sc}=\sqrt{\theta_{sc.in}^2+\theta_{sc.out}^2}$=3 μrad*,**.





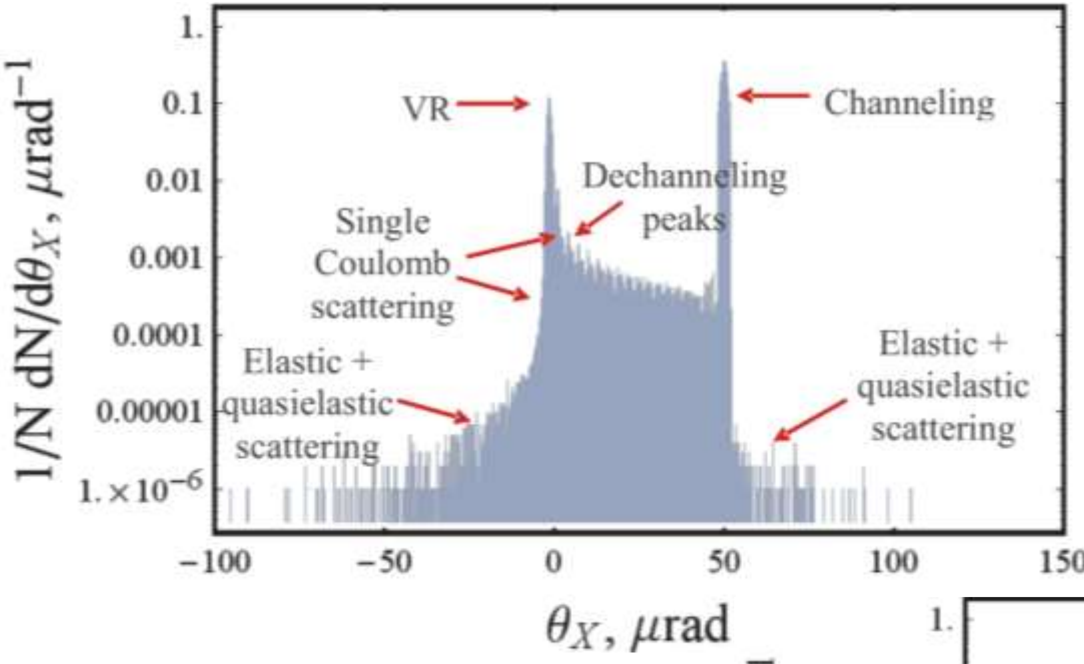
H8 beam line**

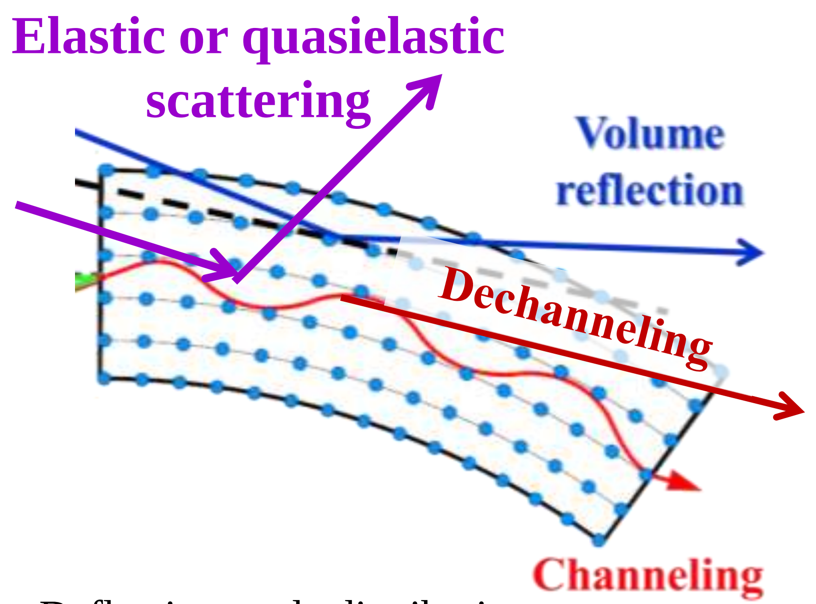


*W. Scandale et al.
Phys. Lett. B 680 (2009) 129–132
** W. Scandale et al.
PRL 101 (2008) 234801.

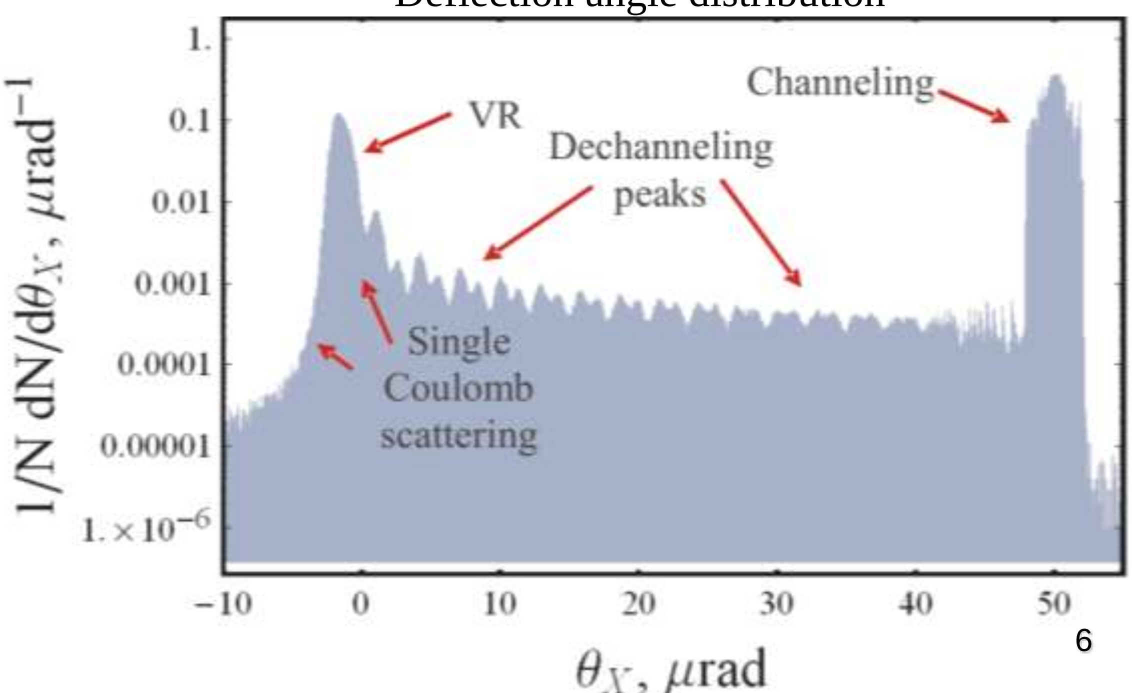
7 TeV proton deflection at the LHC, channeling orientation

Deflection angle distribution





Deflection angle distribution



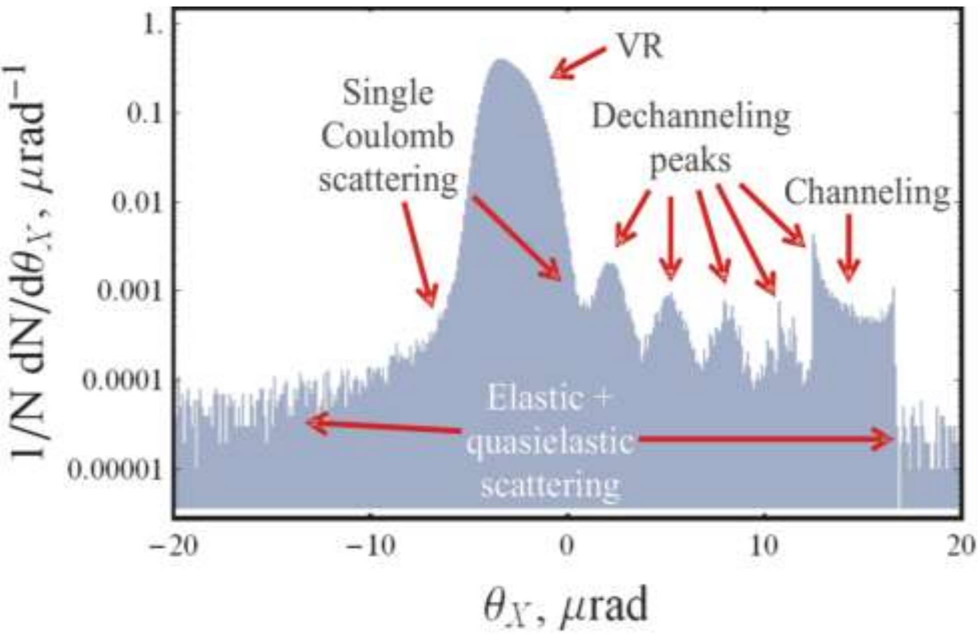
Dechanneling peaks reason: High phase correlation of trajectories.

Crystal parameters*:
l_{cr}=4 mm, θ_b=50 μrad, (110).

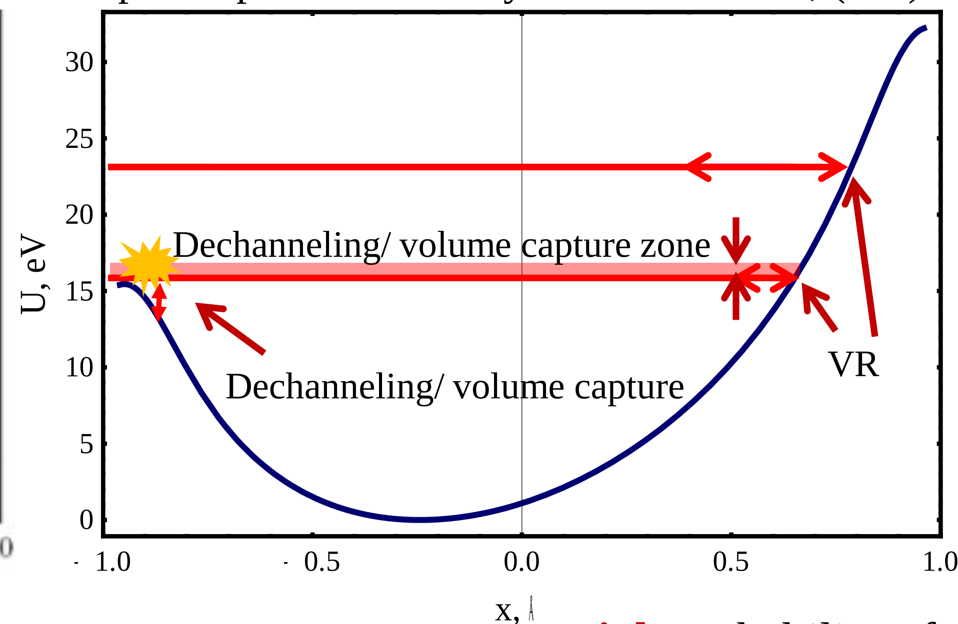
*D. Mirarchi et al.
Proc. of IPAC 2014, P. 882-885.

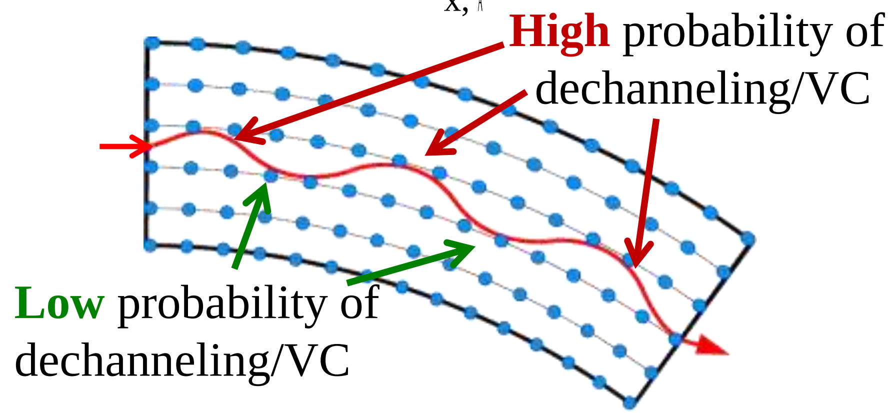
Volume reflection orientation, dechanneling peaks explanation

Deflection angle distribution



Interplanar potential in a crystal with R=80m, (110)





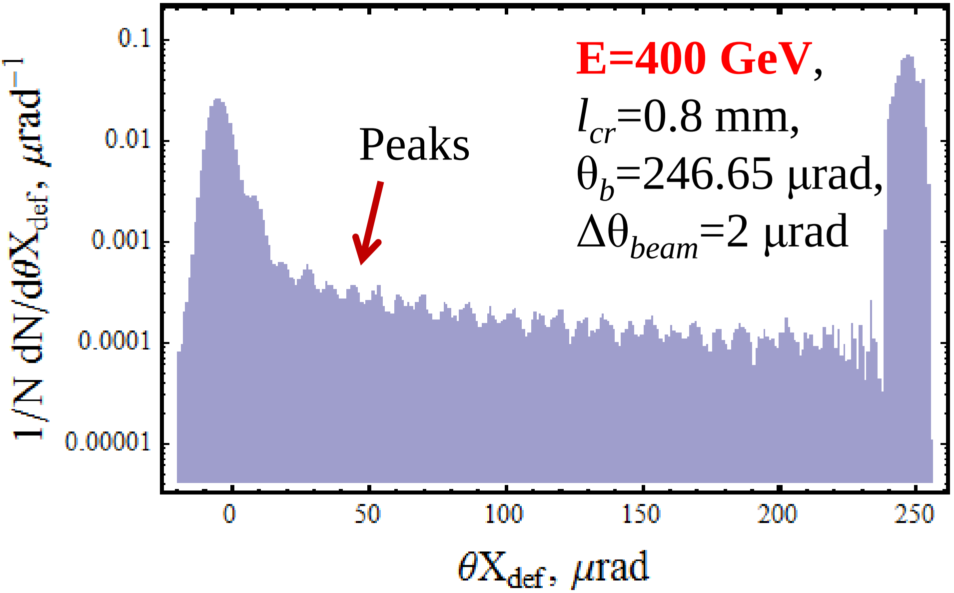
Dechanneling peaks appearance condition:
Scattering angle* on the crystal less than the peak half width:

$$\frac{\Delta\varphi_{peak}}{2\theta_{sc}} = \frac{\lambda\theta_b}{4l_{cr}}\cdot\frac{pv}{13.6MeV\cdot\sqrt{l_{cr}/X_r}\cdot(1+0.038\cdot ln(l_{cr}/X_r))} > 1$$

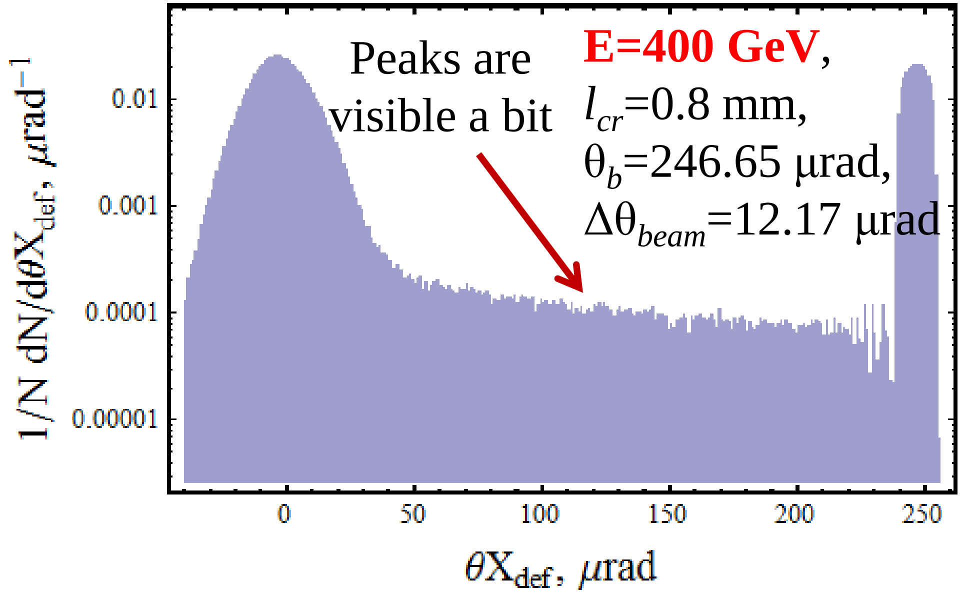
*J. Beringer et al., Particle Data Group

Dechanneling peaks at different energies

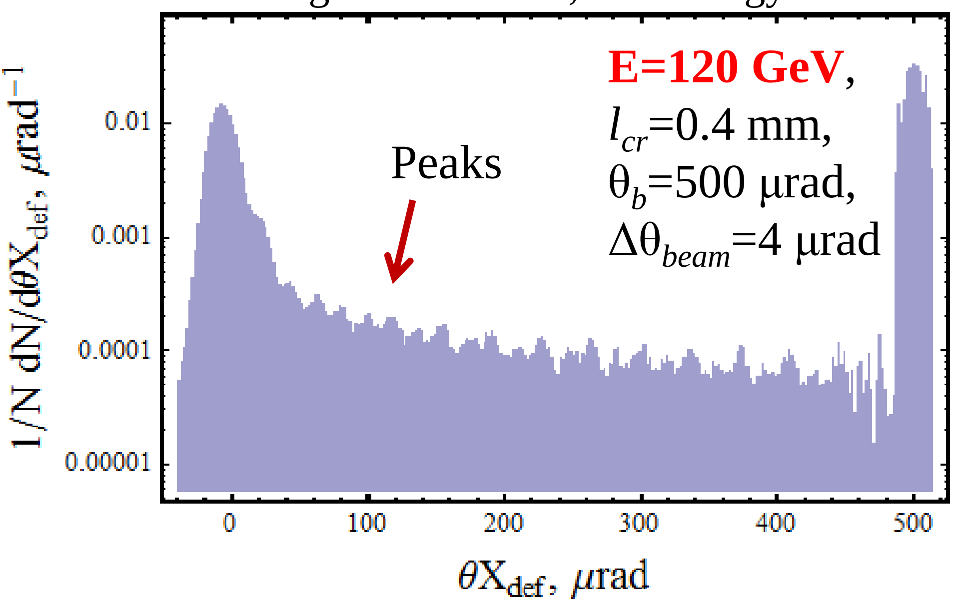
Deflection angle distribution, STF 49 crystal*



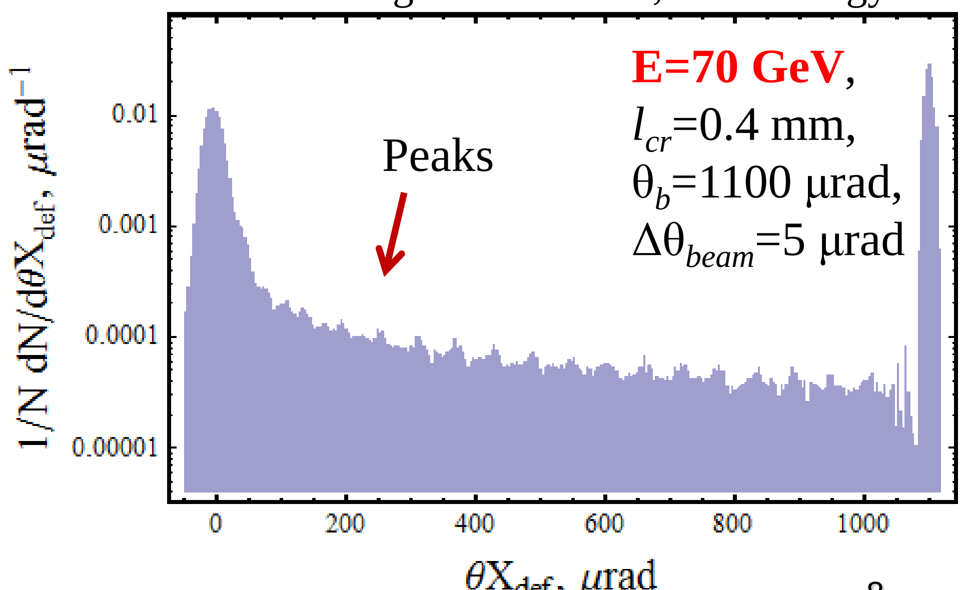
Deflection angle distribution, H8 line, STF 49 crystal*



Deflection angle distribution, SPS energy in UA9*



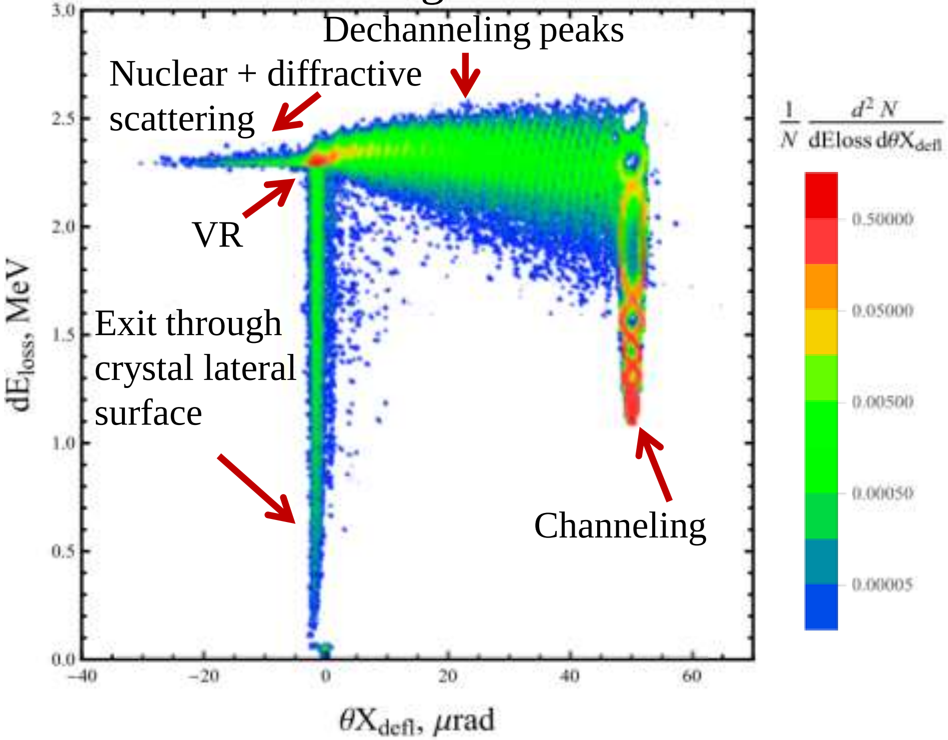
Deflection angle distribution, U-70 energy*



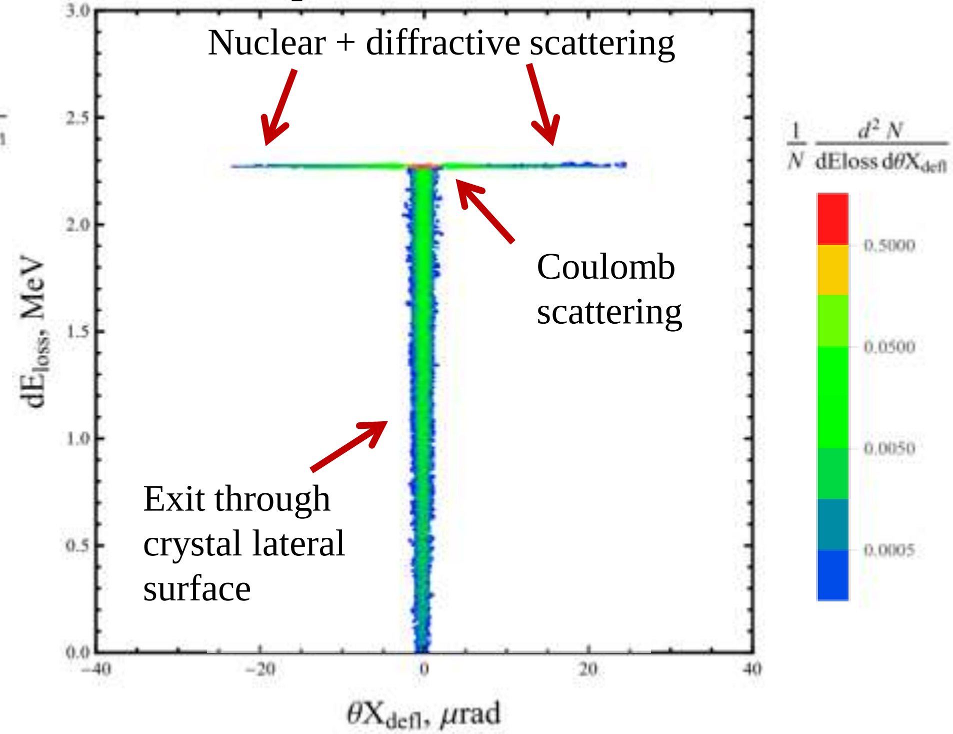
*R. Rossi, H8 Single Pass Test Data Analysis, ColUSM Website

Ionization losses, channeling orientation

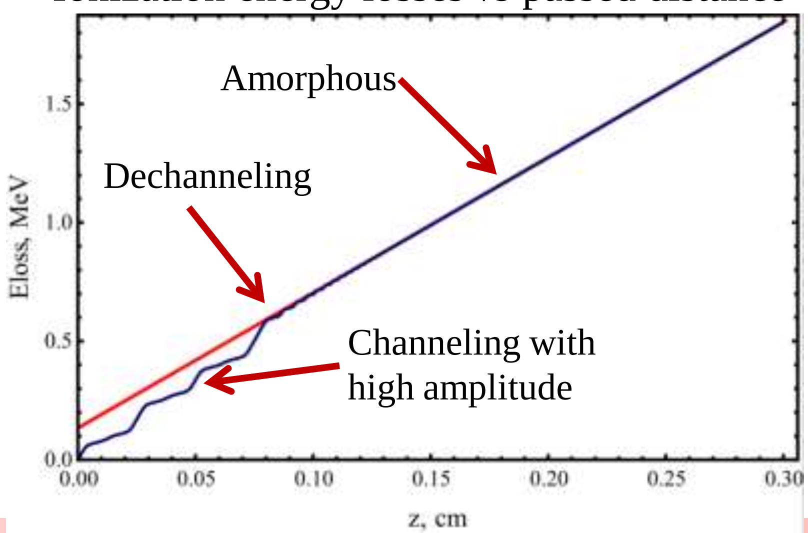
Channeling orientation



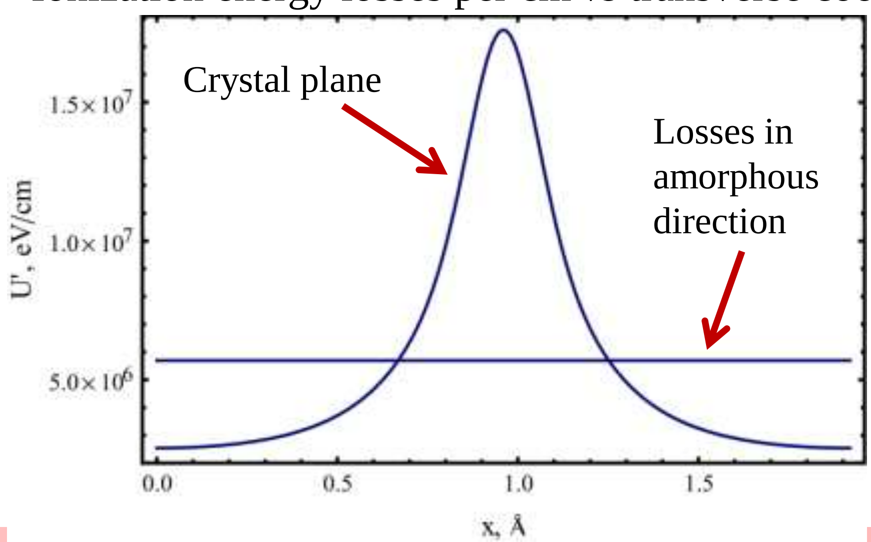
Amorphous orientation



Ionization energy losses *vs* passed distance



Ionization energy losses per cm *vs* transverse coordinate



New effects found in CRYSTAL simulations

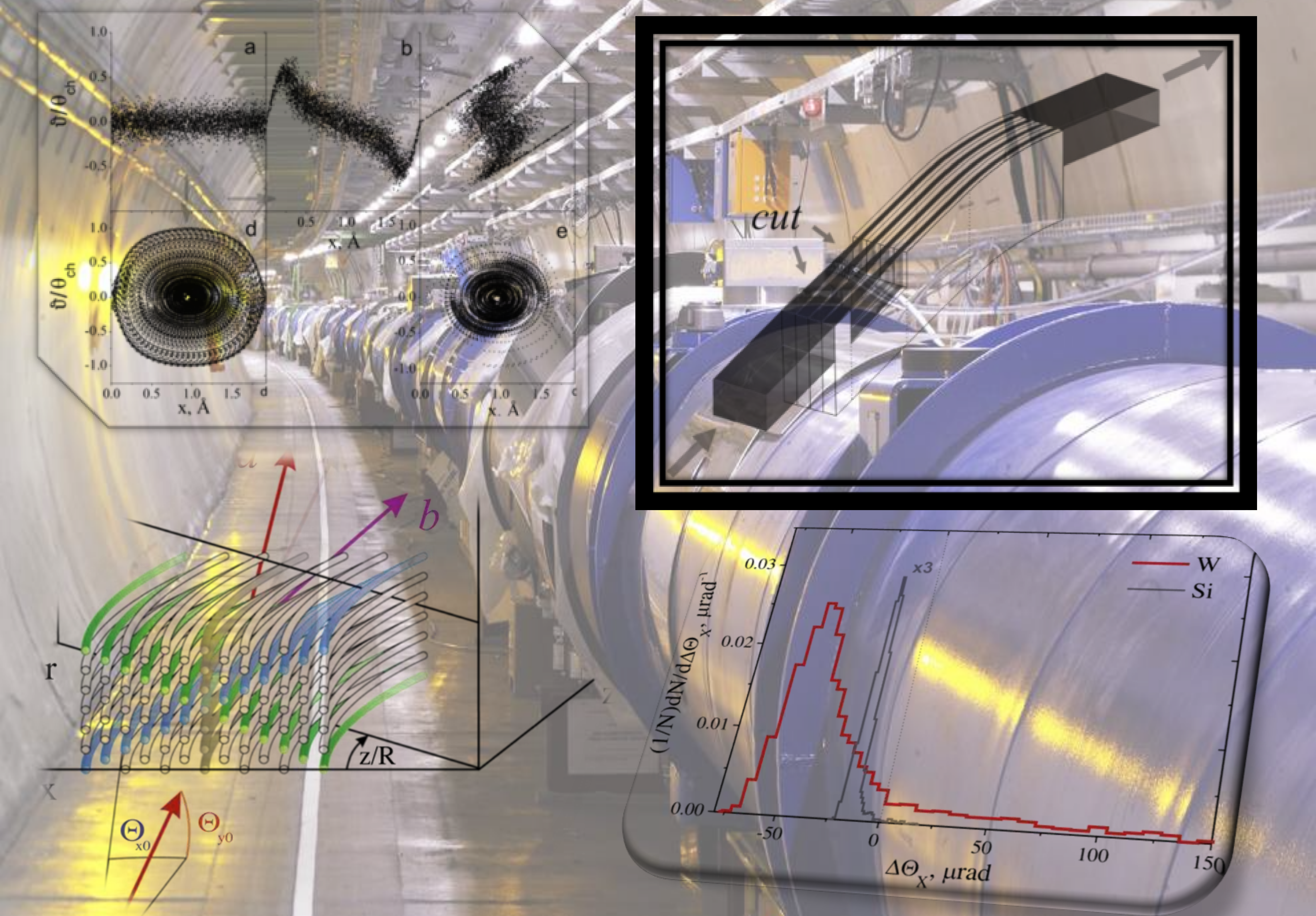
- **Dechanneling peaks** due to high correlation between different trajectories and small scattering angle at the crystal.
  - The effect may be observed in a wide range of energies from hundreds of MeV up to hundreds of TeV.
  - In the crystal-assisted collimation experiment at the LHC it will be naturally observed.
  - The principle condition of its observation is small scattering angle in comparison with the dechanneling peak width

$$\boxed{\frac{\Delta\varphi_{peak}}{2\theta_{sc}} = \frac{\lambda\theta_b}{4l_{cr}} \cdot \frac{pv}{13.6MeV \cdot \sqrt{l_{cr} / X_r} \cdot (1 + 0.038 \cdot ln(l_{cr} / X_r))} > 1}$$

as well as small angular divergence of the incident beam ($\theta_{r.m.s.} < \theta_L/2$).

- **Ionization losses over the amorphous level** are observed in the channeling mode at extremely large amplitudes due to high electron density along the particle trajectory.

New effects for the collimation at the LHC

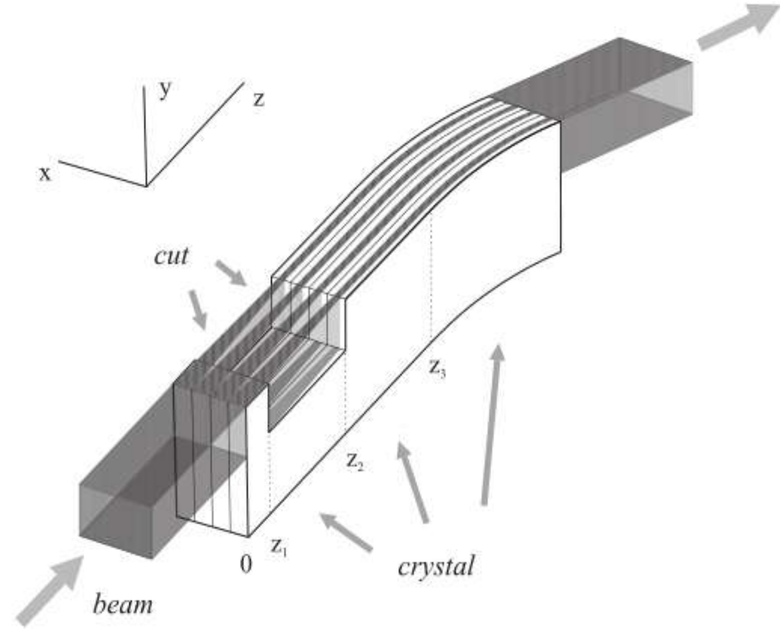


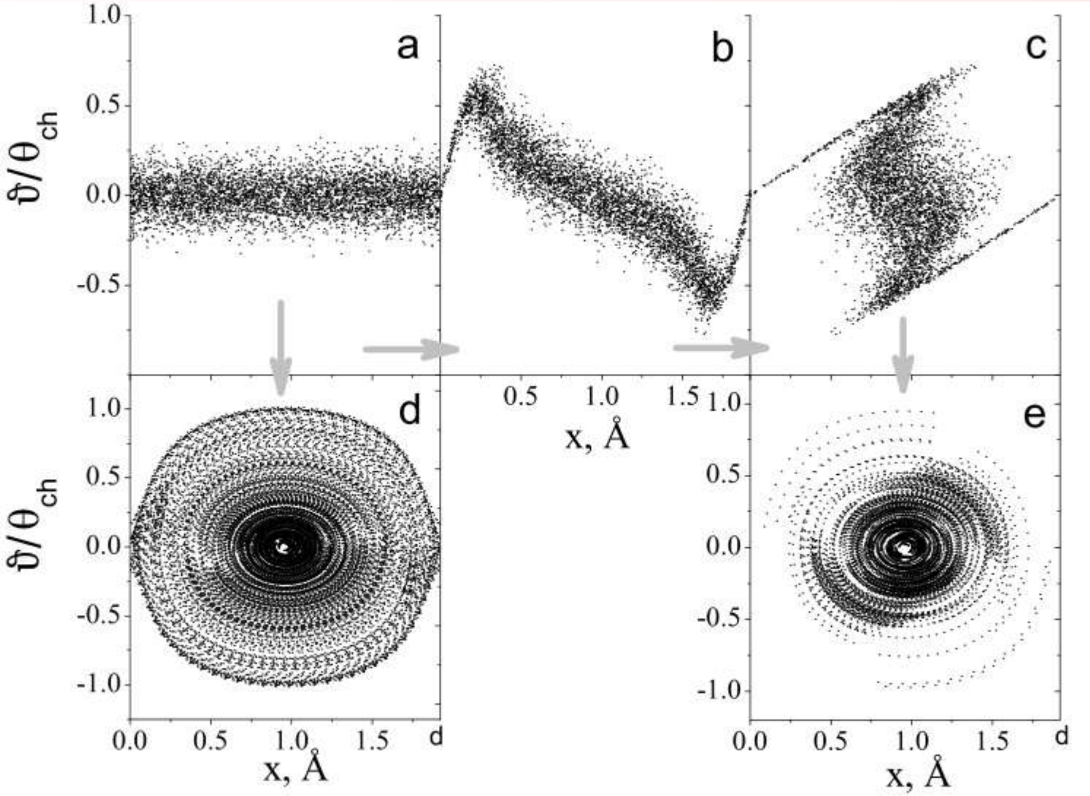
Jinst
PUBLISHED BY INSTITUTE OF PHYSICS PUBLISHING AND SISSA
RECEIVED: *March 22, 2007*
REVISED: *July 9, 2007*
ACCEPTED: *August 15, 2007*
PUBLISHED: *August 22, 2007*

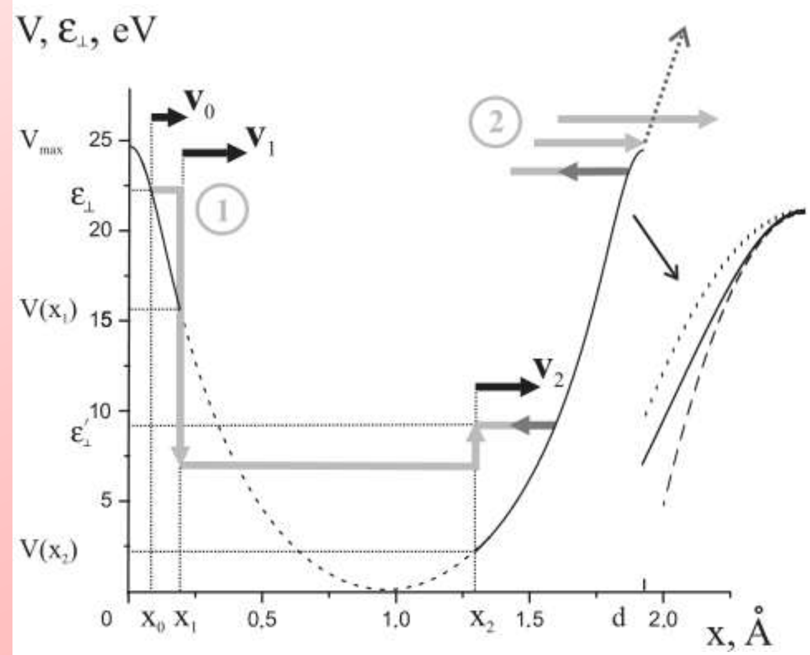
A technique to improve crystal channeling efficiency of charged particles

V.V. Tikhomirov

Research Institute for Nuclear Problems, Belarus State University,
Bobruiskaya 11, 220030 Minsk, Belarus
E-mail: vvtikh@mail.ru



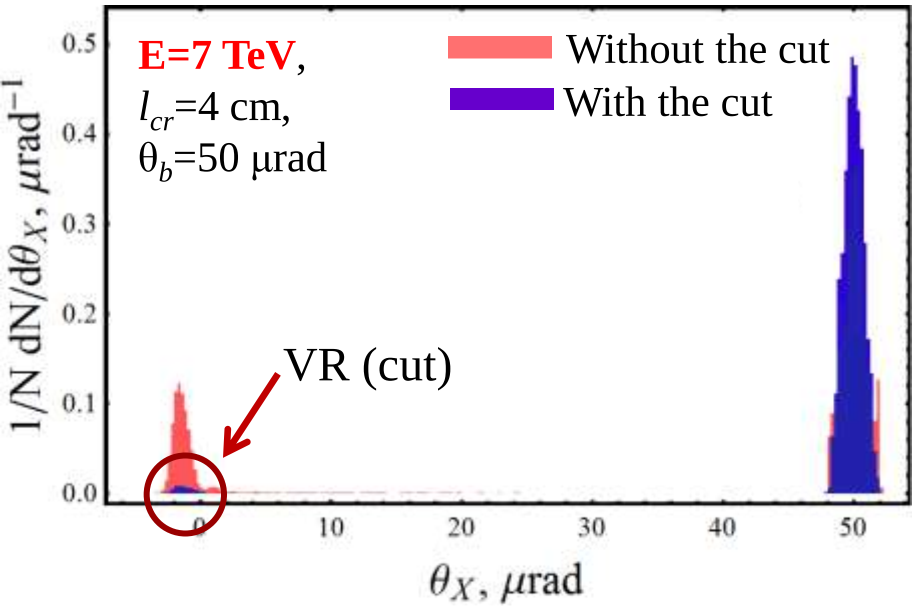




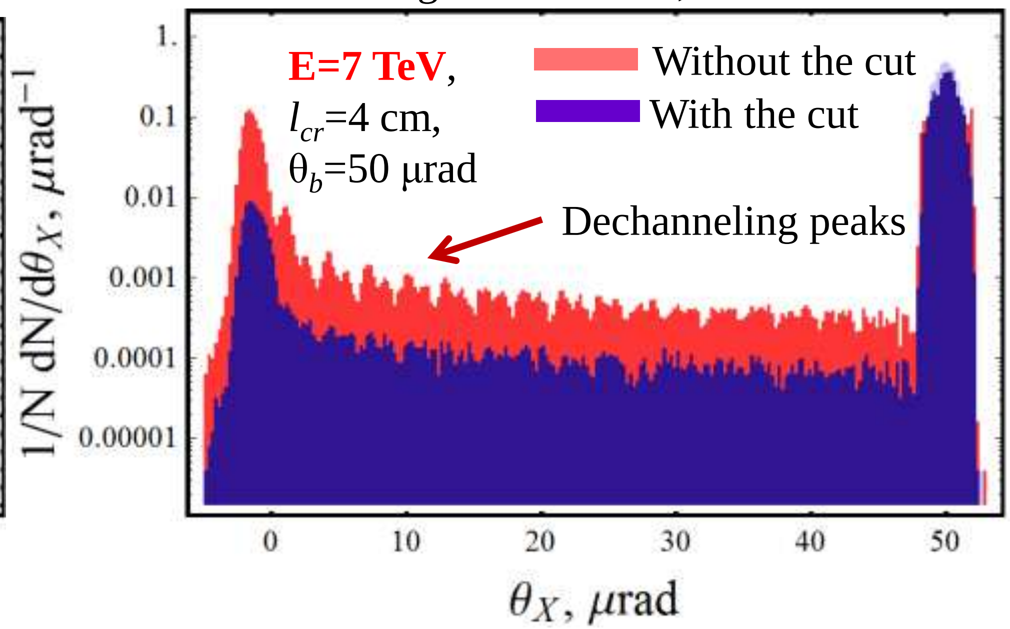
Proton "phase space" a) at $z = 0$, b) at $z = z_1$, c) at $z = z_2$ and e) at $z = z_2+\pi\nu_{\|}/2\omega$ in the cut presence and d) at $z = z_1+\pi\nu_{\|}/\omega$ in the absence of the latter

A technique to improve crystal channeling efficiency for the LHC!

Deflection angle distribution, LHC conditions*



Deflection angle distribution, LHC conditions*



No cut

- Channeling efficiency = **77.7%**
- Deflection efficiency on a collimator = **80%**

Cut

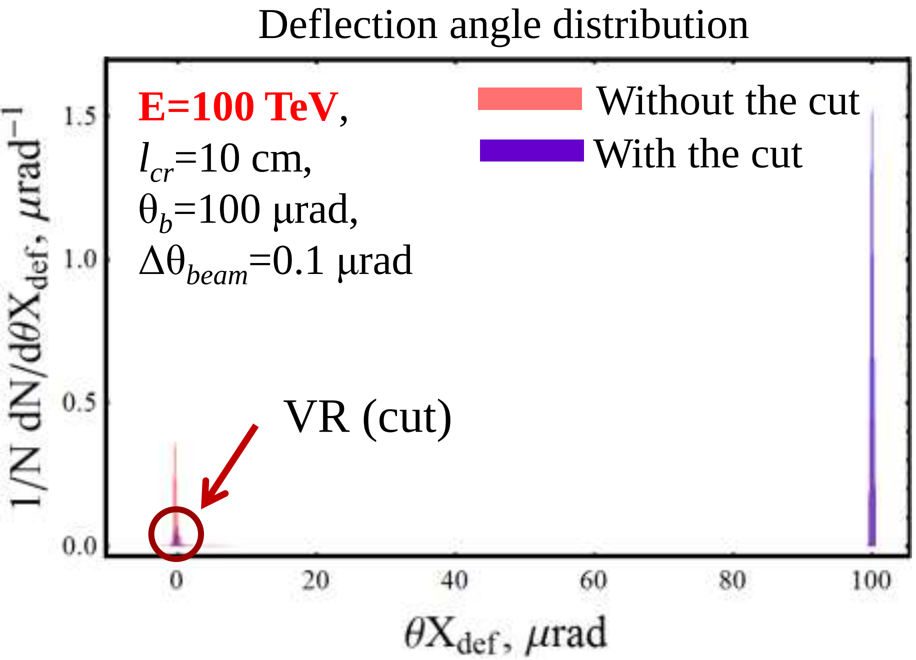
- Channeling efficiency = **97.8%**
- Deflection efficiency on a collimator = **98.2%**

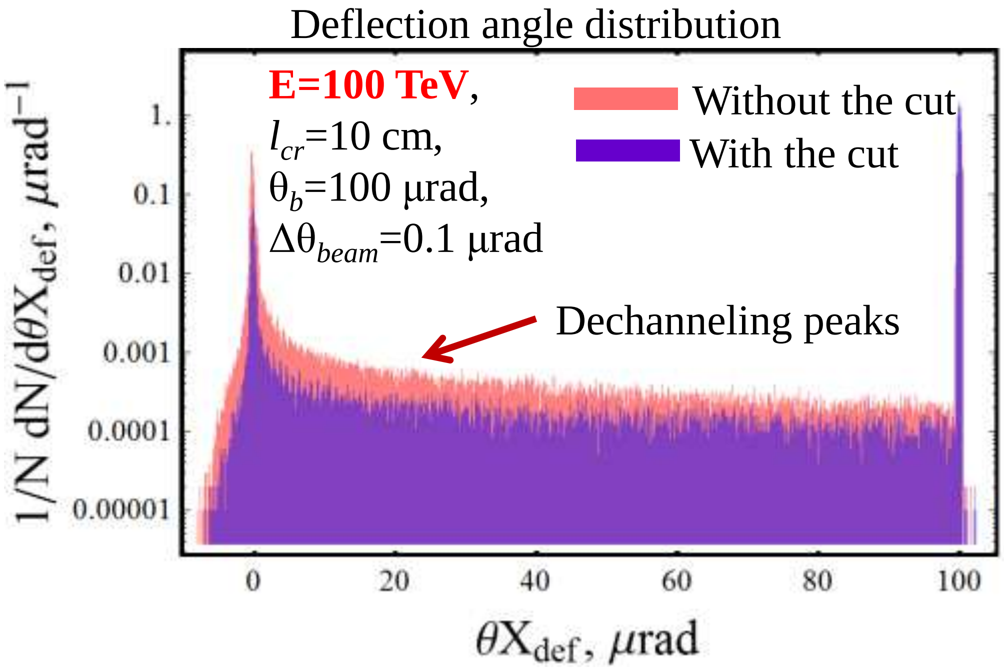
Channeling efficiency increases by **20**%!
Nuclear interactions decrease in **7** times (multiturn simulations)!

Cut parameters: z_1=**17µm**; cut thickness z_2-z_1 **54µm** for the LHC energy. Quite real!

*D. Mirarchi et al. Proc. of IPAC 2014, P. 882-885.

100 TeV Collider*, application of a crystal with the cut





No cut

- Channeling efficiency = **72.6%**
- Inelastic losses = **5.9%**

Cut

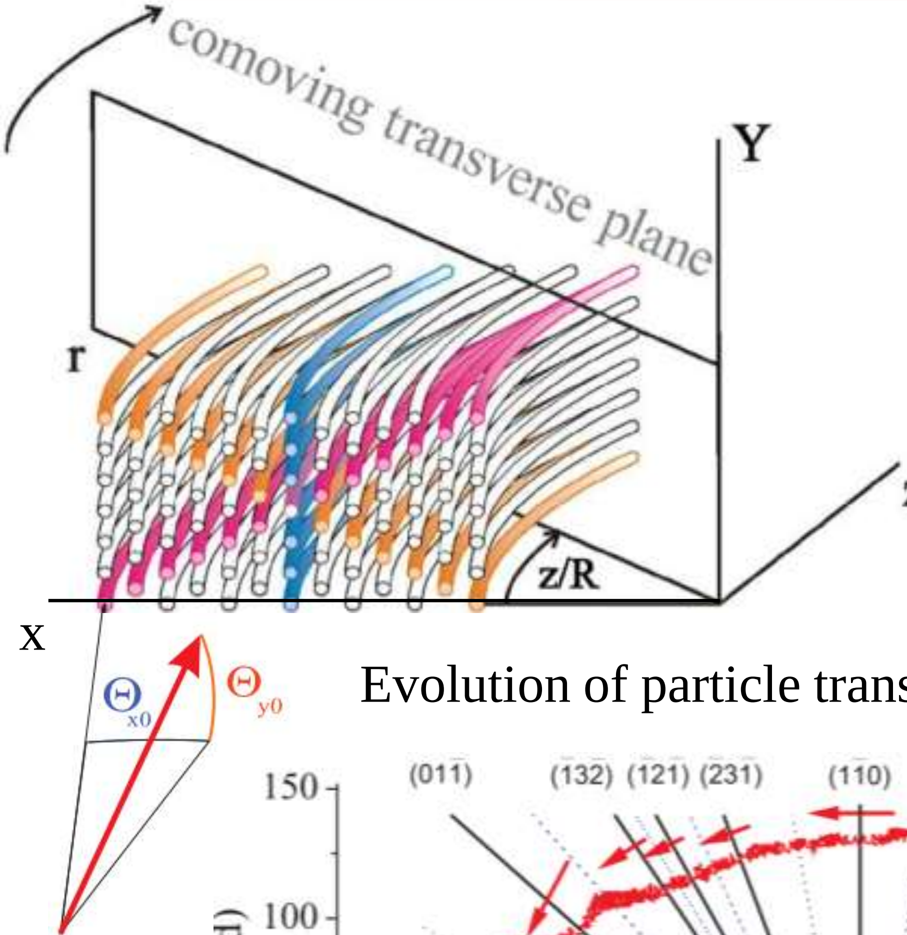
- Channeling efficiency = **92.9%**
- Inelastic losses = **1.8%**

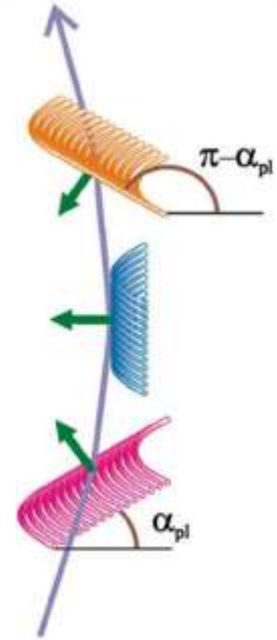
Channeling efficiency increases by **20**%!
Nuclear interactions decrease in **3** times!

Cut parameters: z_1=**65,6μm**; cut thickness z_2-z_1=**212μm** for 100 TeV. Quite real!

*A. Kovalenko, Abstr. of Channeling 2014

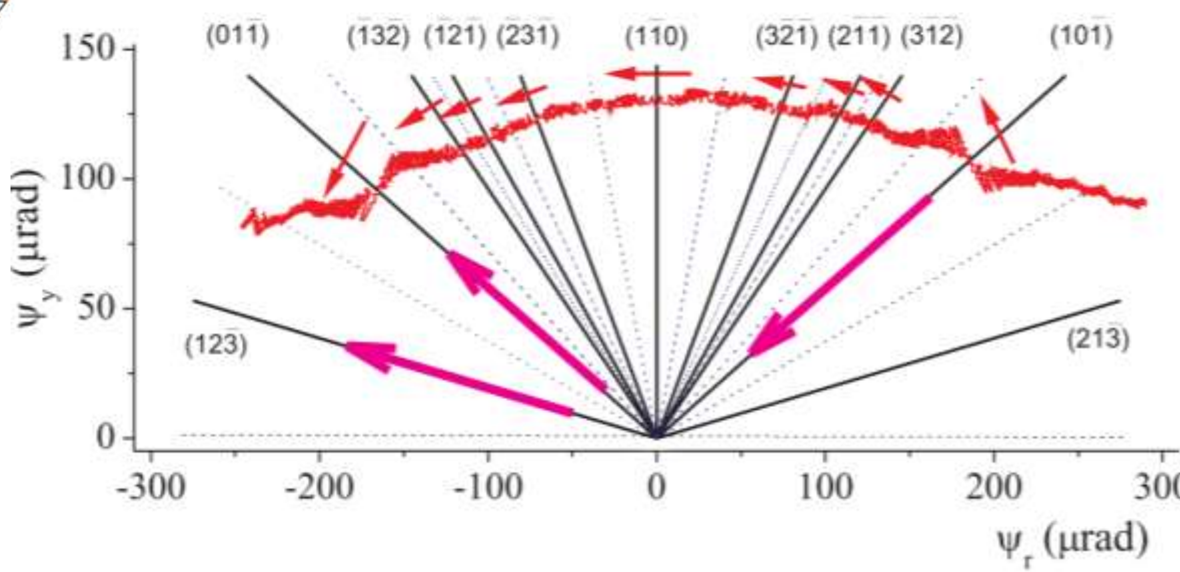
Multiple Volume Reflection in one bent crystal (MVROC)*





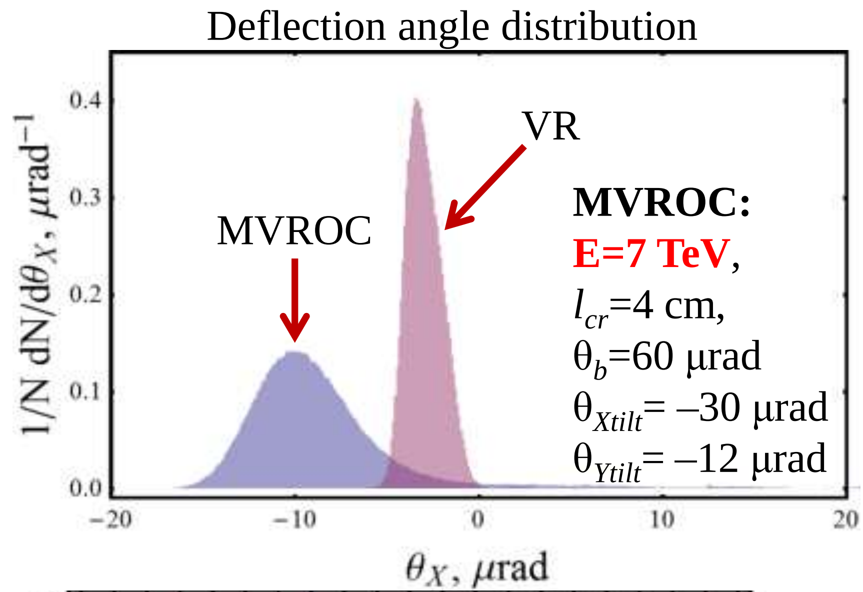
Axes form ***many*** inclined reflecting planes

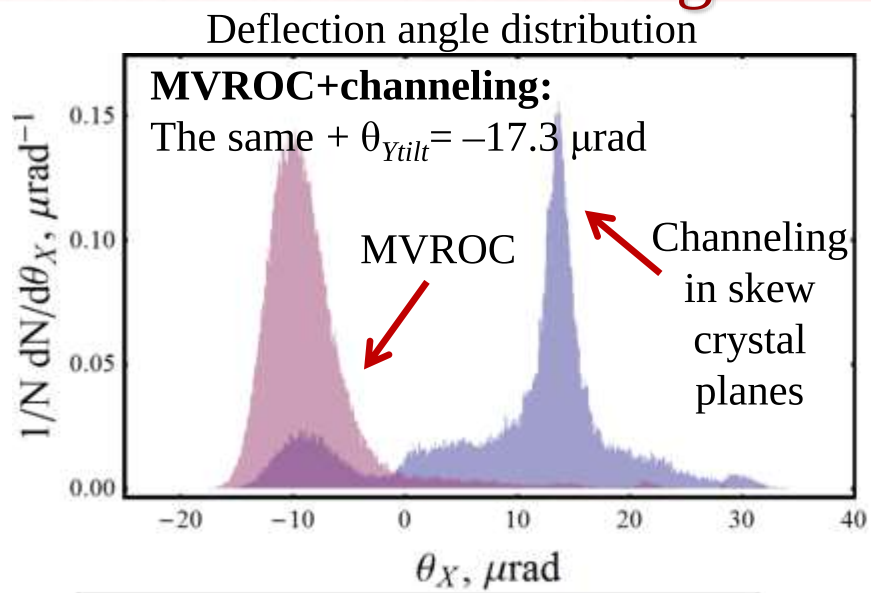
Evolution of particle transverse velocity in the ry plane**

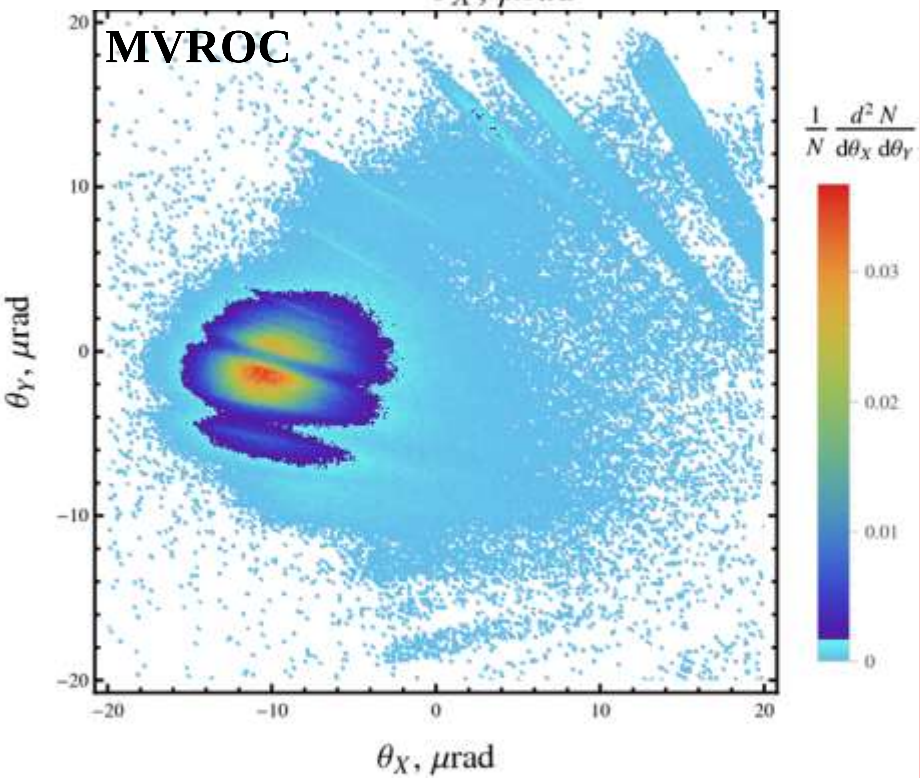


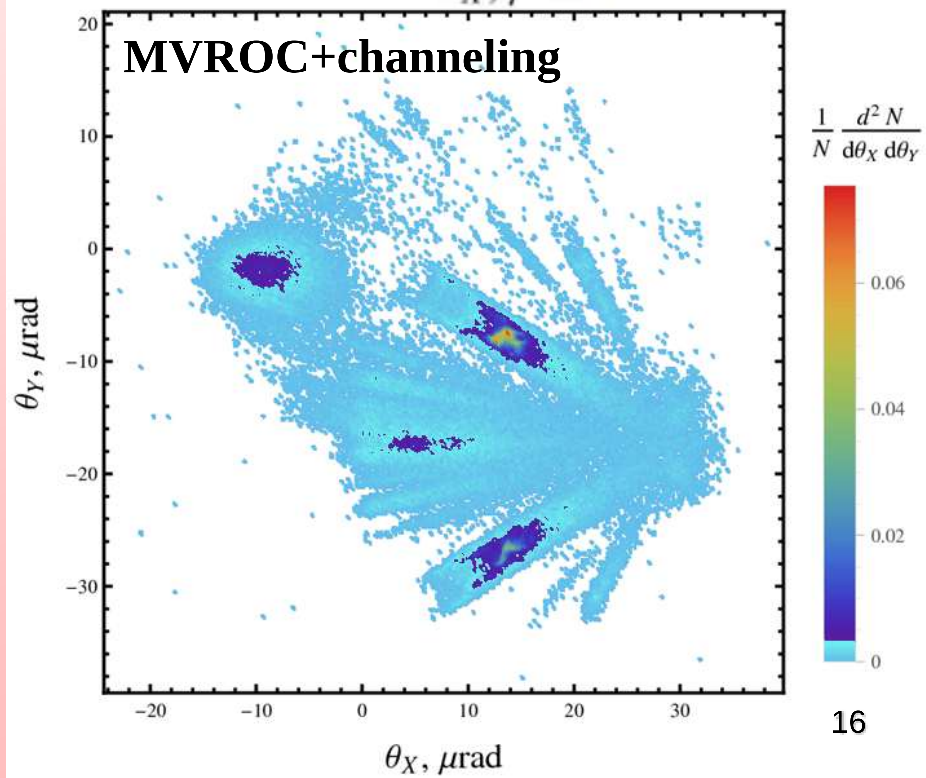
*V. Tikhomirov, PLB 655 (2007) 217; V. Guidi, A. Mazzolari and V. Tikhomirov, JAP 107 (2010) 114908
**V.V. Tikhomirov, A.I. Sytov, NIM B 309 (2013) 109–114.

MVROC and its combined action with channeling



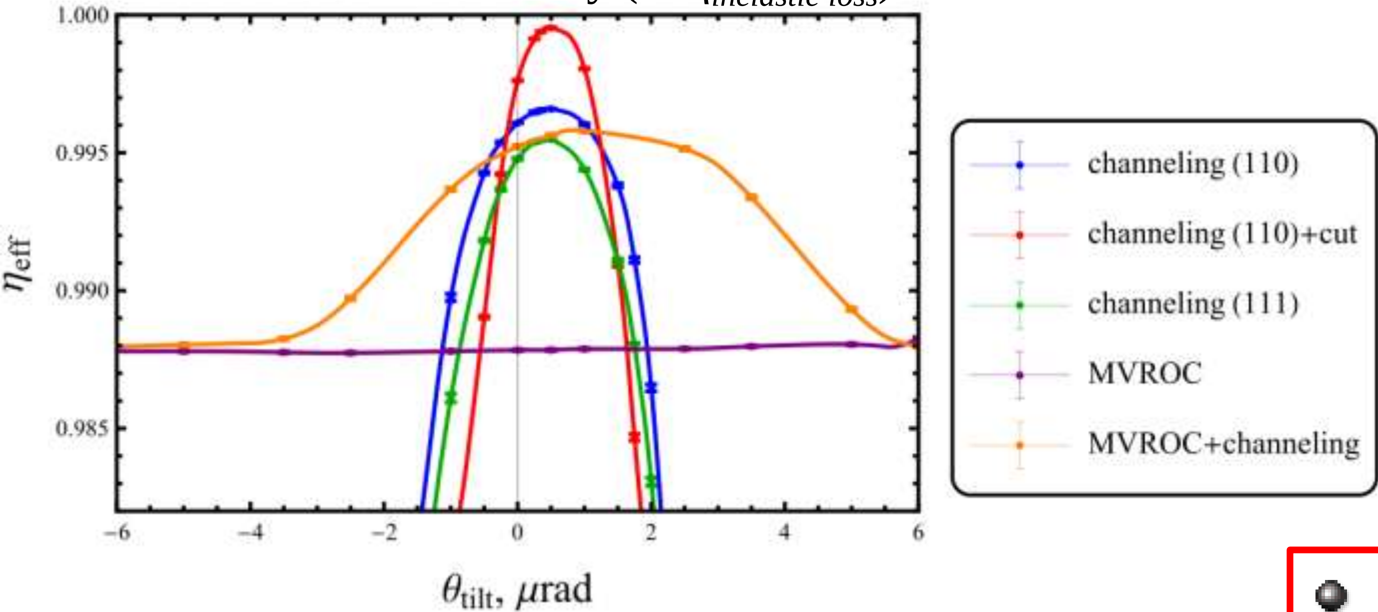






Multiturn simulations by CRYSTAL*

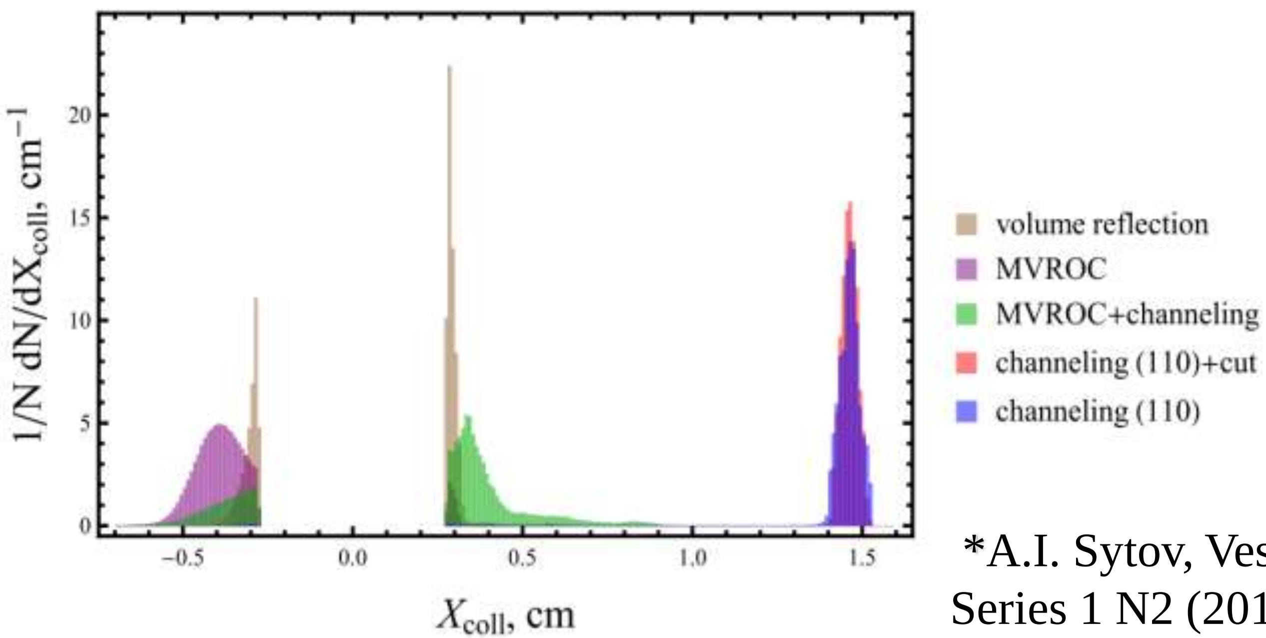
Collimation efficiency (1–$\eta_{inelastic\ loss}$)



E=7 TeV,
l_{cr}=4 cm,
θ_b=50 μrad (channeling)
θ_b=60 μrad (MVROC)

Statistics:
10^5-10^7 particles
at a personal machine
Intel Core i7

Transverse coordinates distribution at the TCSG.6R7.B1



- Collimation efficiency for the crystal with the **cut** achieves **99.95%**!
- Channeling requires alignment resolution of **±0.5 μrad**; otherwise **MVROC combined with channeling** is more effective.

*A.I. Sytov, Vestnik. Belarusian. Univ. Series 1 N2 (2014), 48-52, (in Russian).

Summary

- **CRYSTAL** program for the simulation of particle trajectories was developed.
- The **H8 experiment** was simulated; a good agreement was achieved.
- The new effects found in simulations were predicted for the LHC: **dechanneling peaks** and **ionization losses over the amorphous level**. The reason of the first effect is very high correlation of different trajectories. The reason of the second effect is high electron density along the particle trajectory.
- The application of the **crystal cut** allows to reduce the inelastic loss rate in several times for both the LHC an 100 TeV Collider. In addition it increases the channeling efficiency on **20%** for both of the cases.
- The **MVROC** effect as well as its combination with channeling in skew crystal planes is a good alternative to channeling at the LHC.

BSU

INP

Thank you for attention!