Update on the modelling of crystal channeling for FLUKA

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Ref. : Monte Carlo modeling of crystal channeling at high energies

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Outline

- Introduction
- Description of the model
  - Frame of reference
  - Continuous potential
  - Interactions in Channeling
  - Volume effects
  - Exit kick
- Results
  - 2D distributions – Case study
  - Benchmarking against UA9-H8 data
- Conclusions

Introduction

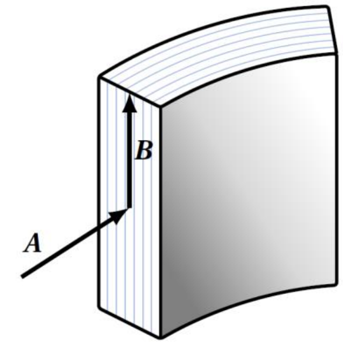
- **Why an implementation of channeling inside FLUKA ?**
  - Crystals are investigated as new possible solution for collimation @ CERN
  - Energy deposition and tracking of secondaries need to be evaluated
  - FLUKA is the Monte Carlo currently used to assess these values in the collimation system

- **How does it work ?**
  - Microscopic description avoiding the use of empirical parameters
  - Crystals defined as a region of the FLUKA geometry layout in which
    - Particles can be channeled if their transverse energy is small enough
      - Follow channel curvature
      - Undergo reduced amount of interactions
    - Interactions are carried on using FLUKA models
    - Quasi-channeled particles can be reflected or captured

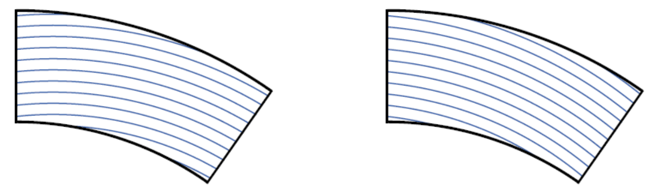
Presently, a standalone event generator has been developed and benchmarked.
Integration into FLUKA not yet completed.

Frame of reference

- **Crystal defined in FLUKA combinatorial geometry**
  - Object situated in the laboratory
  - Region flagged as crystal → trigger channeling-related effects

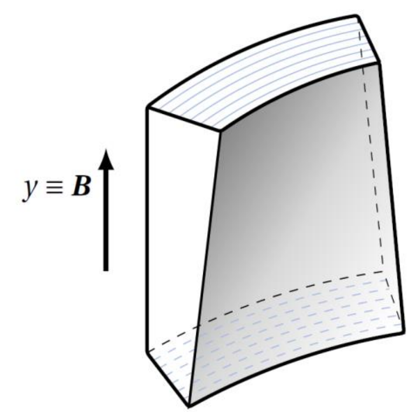


- **Crystal planes defined inside crystal by 2 vectors**
  - ***A*** : along the channel direction
  - ***B*** : perpendicular to ***A***, giving the crystal planes orientation
  - Vectors are independent from the region
    - Natural reproduction of miscut



(a) (b)

- **Torsion**
  - Change in the channel orientation along ***B***
  - Change the radius of curvature proportional to excursion along ***B***

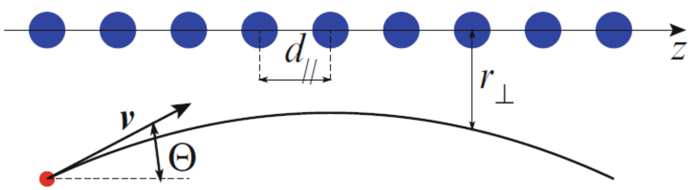


Continuous Potential in a Crystal

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

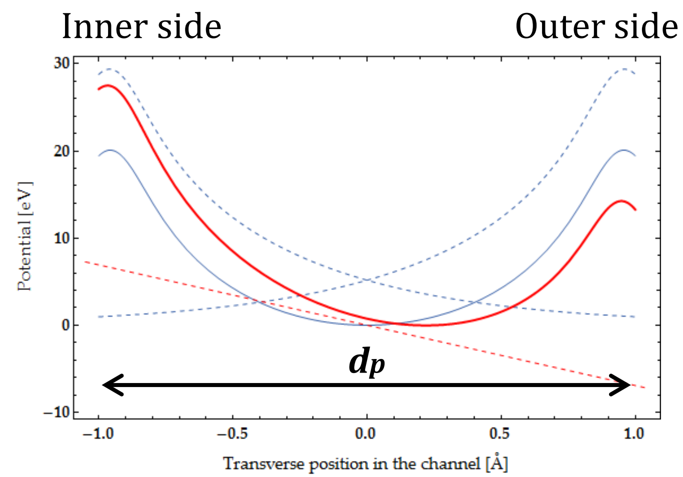
1. Straight crystal

- Lindhard formalism
  - For small incoming angles relative to the crystal planes, successive interactions of the particle with the lattice plane are correlated.
  - Hence, we consider interactions with the plane as a whole
  - « Continuous » strings of atoms → Continuous potential
- Moliere screening function
- Thermal vibrations
  - Average the cont. pot. over the gaussian thermal motion
  - RMS amplitude u_T = 0.075 Å at room temp.



2. Bent crystal

- Centrifugal Potential $U_c(x) = -\frac{pv}{R}x$
- The effective potential barrier is reduced on the outer side
  - For a certain bending, the potential well does not exist anymore
  - → *critical radius*
- Effective Potential



$$\boxed{U_e(x) = U_{pl}\left(x + \frac{d_p}{2}, u_T\right) + U_{pl}\left(x - \frac{d_p}{2}, u_t\right) + U_c\,(x)}$$

3. Channeling condition

- Energy of the transverse motion

$$E_x = \frac{p_x^2 c^2}{2E} + U_e(x) \approx \frac{pv}{2}\theta_x{}^2 + U_e(x)$$

- Potential Energy ?
  - depends on the initial transverse position
  - random variable, uniform over $\left[-\frac{d_p}{2}, \frac{d_p}{2}\right]$

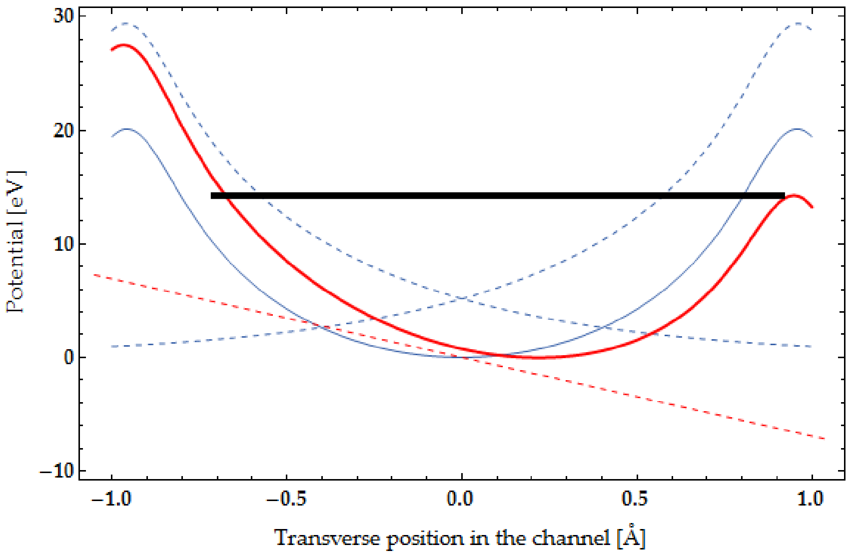
- Particle is channeled if :

$$\boxed{E_x \leq U_e\left(\frac{d_p}{2}\right)}$$

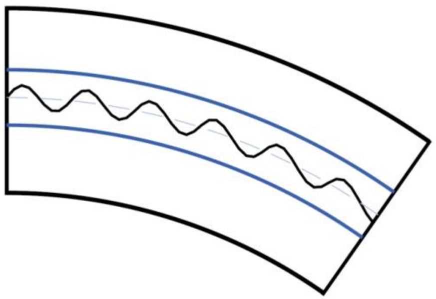
- Maximal θ_x angle allowing channeling in a given crystal at a given energy

  = *critical angle*

$$\theta_c = \sqrt{\frac{2U_e(d_p/2)}{pv}}$$

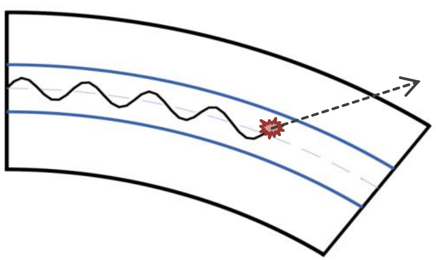


Interactions in channeling



1. Oscillations

- Particle oscillate between planes
  - Approx. : Harmonic potential
  - → Sinusoidal oscillations
- Oscillation amplitude x_m depends on E_x



2. Coulomb scattering

- CH particles → single-scattering mode
- Transverse energy modified by interactions
- According to x_m, interaction with nuclei can be rejected
  - Classical view : particle never comes closer to the lattice than $r_f = \left(\frac{d_p}{2} - x_m\right)$
  - Quantum form factor relating the momentum transfer and impact parameter
- Electrons taken into account through the Fano correction

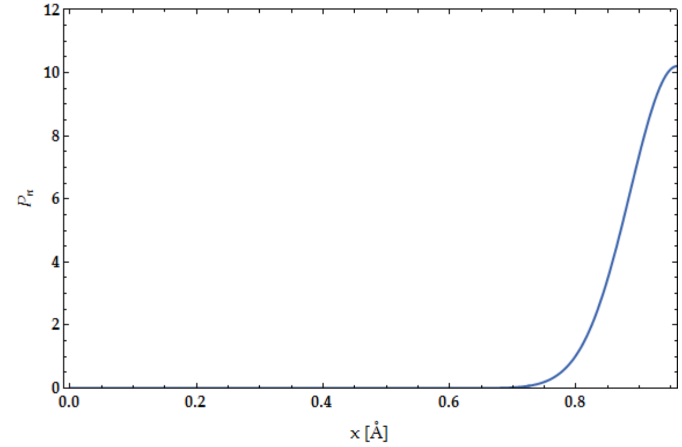
$$F_{\mathrm{f}}(qr_{\mathrm{f}}) = 3\frac{\left[\sin\left(\frac{qr_{\mathrm{f}}}{\hbar}\right) - \frac{qr_{\mathrm{f}}}{\hbar}\cos\left(\frac{qr_{\mathrm{f}}}{\hbar}\right)\right]}{\left(\frac{qr_{\mathrm{f}}}{\hbar}\right)^3}$$

→ Dechanneling if E_x goes above $U_e\left(\frac{d_p}{2}\right)$

2. Nuclear Interactions

- Scaling factor to the cross sections
- = average nuclei density
- Nuclear density in the channel :

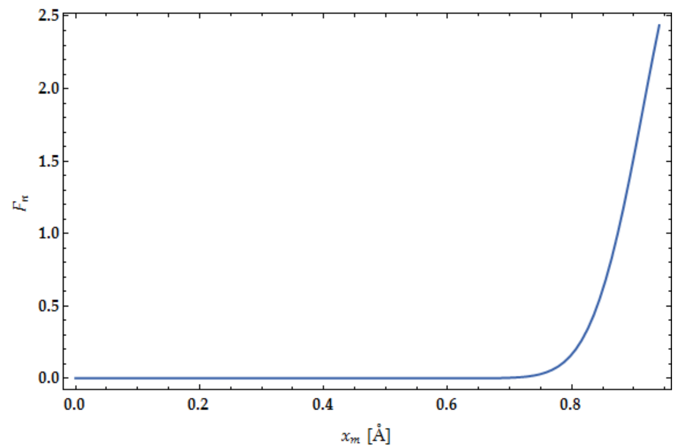
$$P_n(x) = \frac{d_p}{\sqrt{2\pi u_t^2}} \exp\left(-\frac{(d_p/2 - x)^2}{2u_t^2}\right)$$



(a)

- Folding of the density over the sine trajectory

$$F_n = \frac{d_p}{\sqrt{2\pi u_t^2}} \frac{1}{\pi} \int_0^{\pi} \exp\left(-\frac{(d_p/2 - x_m \sin(\varphi))^2}{2u_t^2}\right) \mathrm{d}\varphi$$



(b)

- Typical scaling factors range from 0 to 2.5 for individual particles

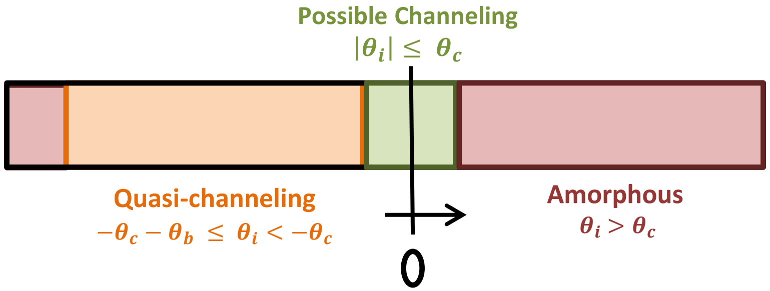
- Reduction rates of the order of 12

For 400GeV/c p^+, R=13m, $\sigma_{x'}$ = 10 urad

Volume effects

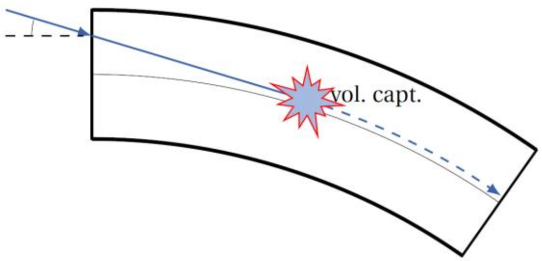
1. Quasi-Channeling

- Non channeled particles
- Crystal bending → Tangency at some point
- Single-scattering mode



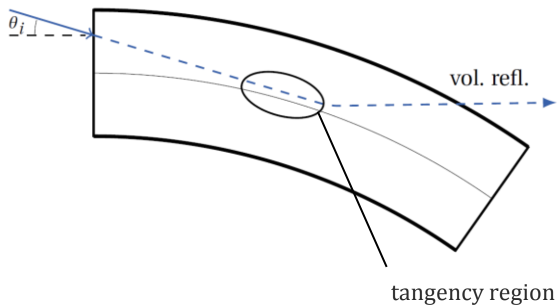
2. Volume capture

- Tangency region begins when $\theta_x \leq \theta_c$
  - $E_x \geq U_e(d_p/2)$
- Transverse energy E_x associated with the quasi-channeled particle
- E_x can be modified by Coulomb scatterings
- **IF** : E_x drops below $U_e\left(\frac{d_p}{2}\right)$ → CAPTURE



3. Volume reflection

- **IF NOT** : Particle escapes the region and is reflected
- One-time kick towards the outer side of the bend

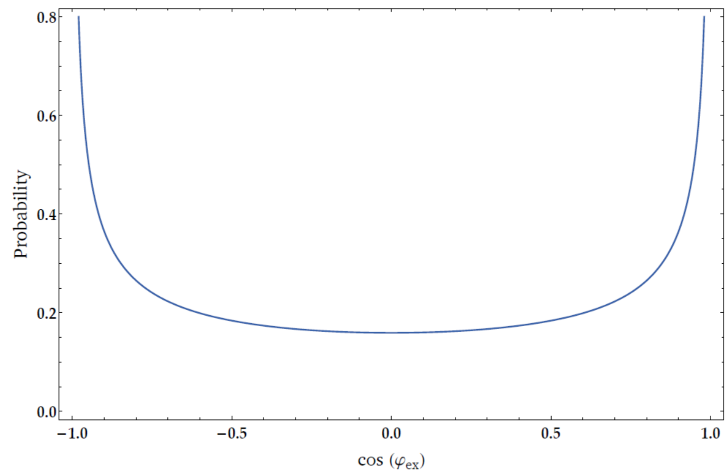


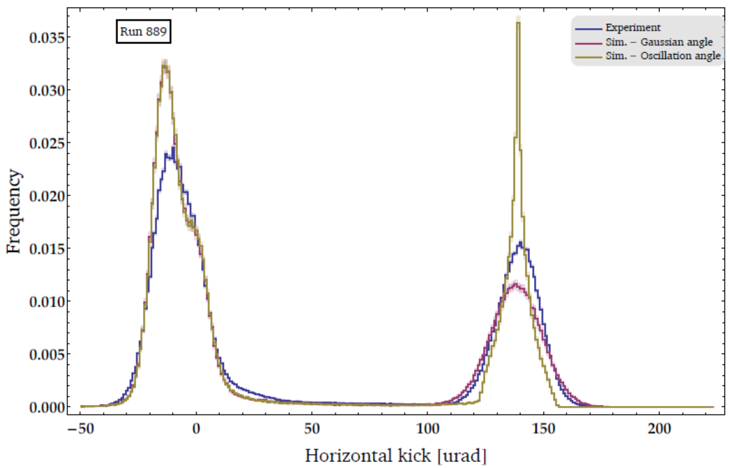
$$\theta_{\text{v.r.}} = -\frac{\pi}{2}\theta_c\left(1 - \frac{2R_c}{R}\right)$$ [M. Bondarenco, arXiv:0911.0107v3, 2010]

- Exception : non-channeled particles with $|\boldsymbol{\theta_i}| \leq \boldsymbol{\theta_c}$ (Thanks to Daniele for pointing this out !)
  - VR kick gradually increasing

Exit kick

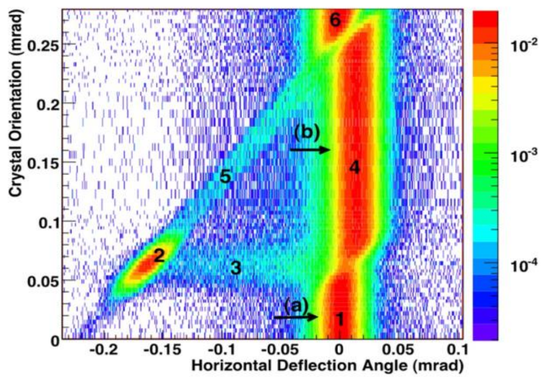
- **A particle exits channeling mode when**
  - it is dechanneled or
  - it exits the crystal region of the geometry
- **Angular spread at exit ?**
  - Natural angle of the oscillating particle
    - Arc sine distribution
    - Width of the distribution depending on the oscillation amplitude of the particle, itself depending on the transverse energy value
    - Results in a steep exit distribution
  - Gaussian angle with $\sigma = \theta_c$
    - Provides satisfying results wrt the experimental data
    - BUT : parameter-related (even though not an entirely arbitrary parameter)
    - Currently the adopted method



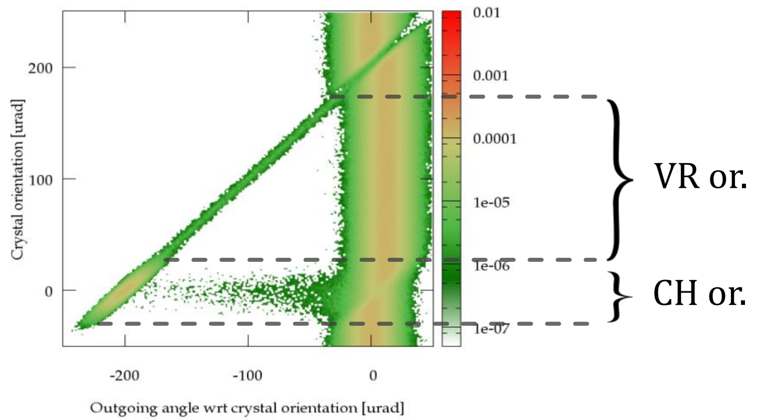


Results

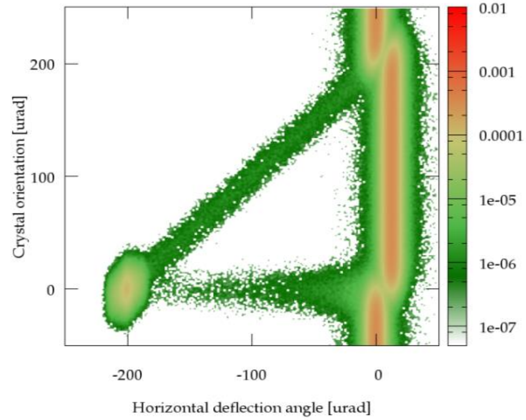
- **Qualitative comparison of angular scan with H8-RD22**
  - Distribution of particles against crystal orientation and hor. outgoing angle wrt crystal orientation (out-cr)
  - Strip crystal in 400 GeV proton-beam – divergence $\sigma_{x'}$=8 urad



[Scandale, PRL **98**, 2007]

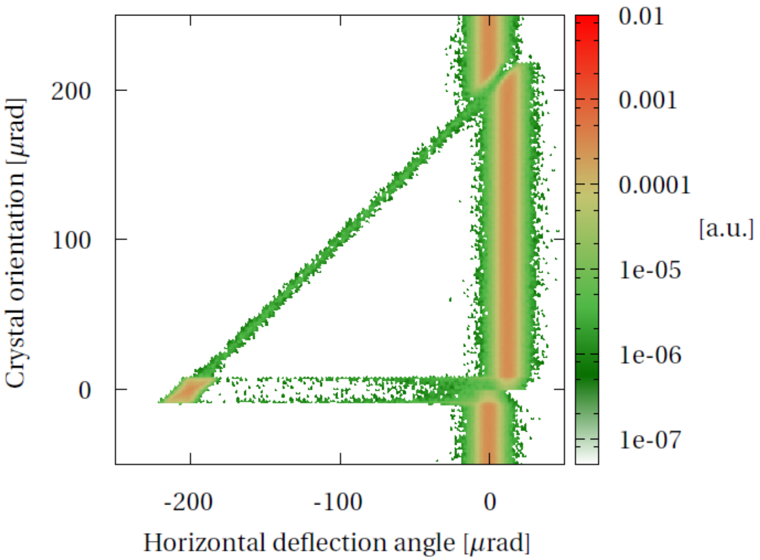


  - Using the hor. Kick (out-in) we have

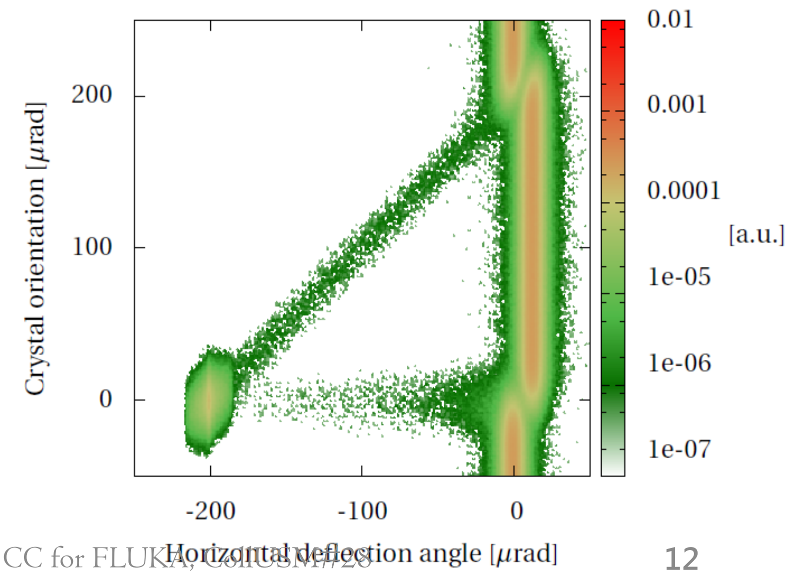


Results

- **Other examples:**
  - *X* divergence = 0

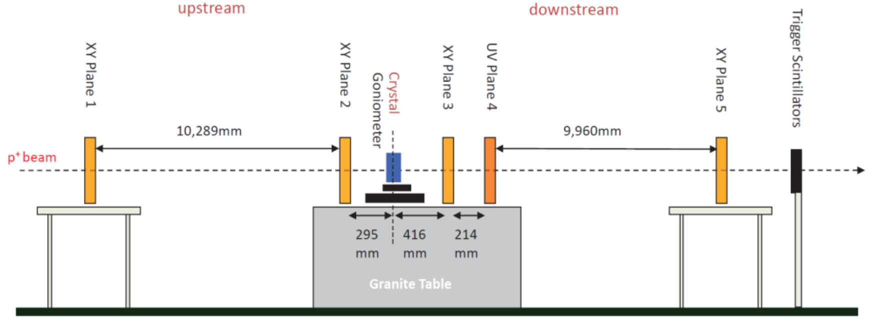


  - With strong torsion (10urad/m), no hor. Divergence, σ_y=1 mm $\sigma_{y'}$=10 urad



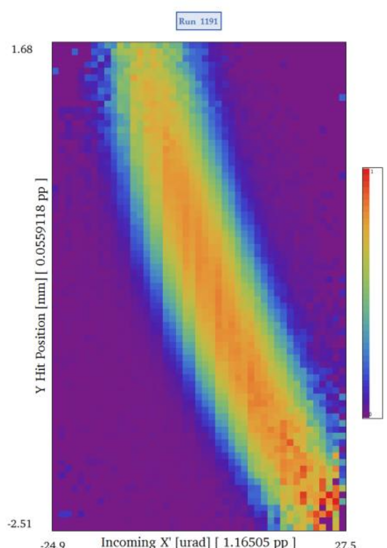
Results

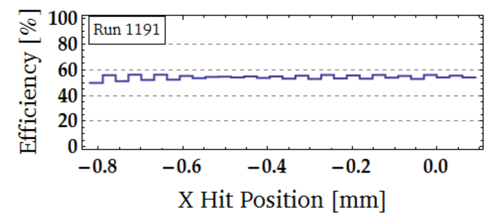
- **UA9-H8:**
  - Single-pass experiment
  - Crystal placed in the center
  - 5 silicon strip detectors around
  - Track reconstruction : up- and downstream
    - → yields deflection angles

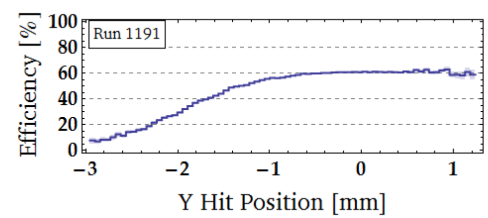


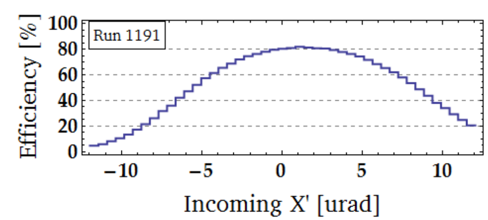
courtesy M. Pesaresi

- **(Preliminary) data analysis:**
  - Determination of the crystal torsion
  - Crystal efficiency after torsion compensation



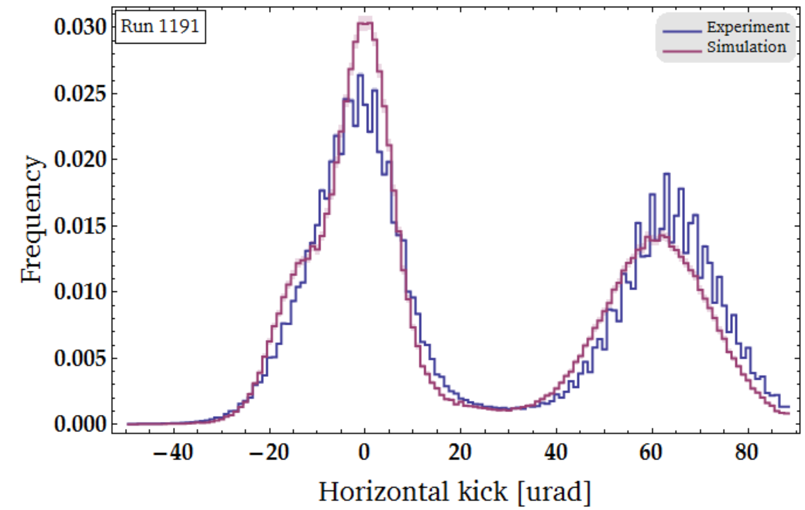


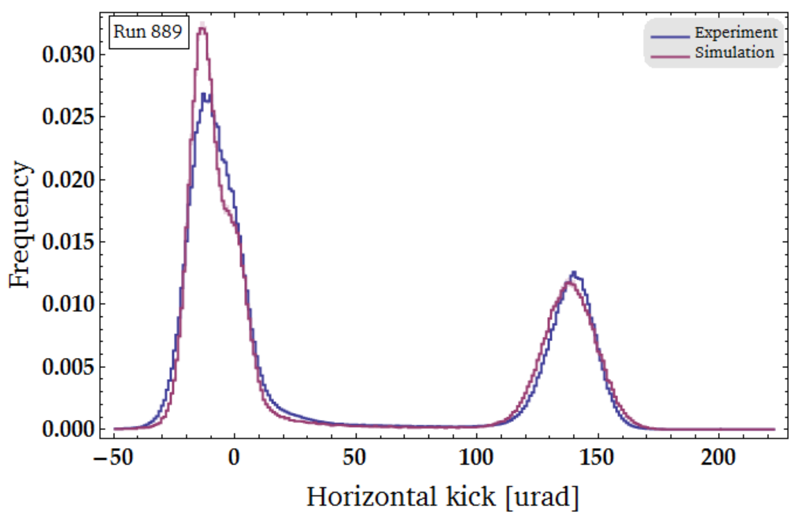


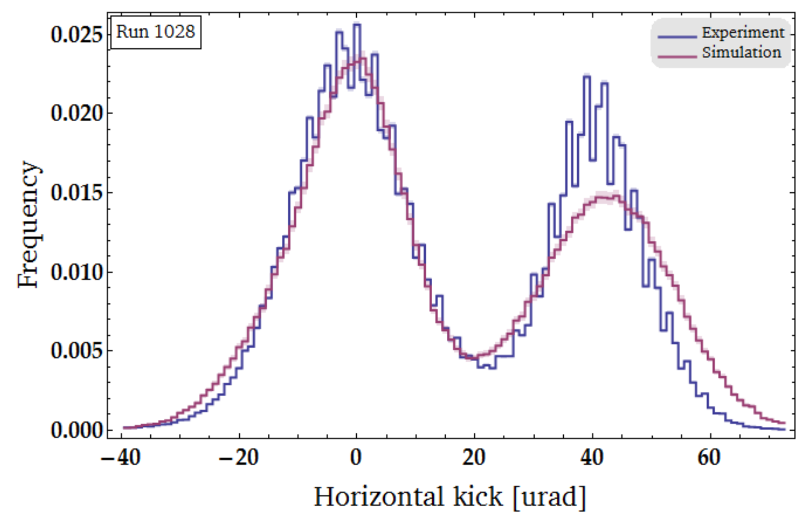


Results

- **Benchmarking against UA9-H8 data : channeling orientation**
  - 2 different types of crystals
    - Quasi-Mosaic
    - Strip
  - Bending angle
    - ~50 urad for LHC
    - ~100-200 urad for the SPS
  - LHC strip crystal (STF 71 – R.1191)
  - SPS strip crystal (STF 50 – R.889)
  - LHC QM crystal (QMP 28 – R.1028)

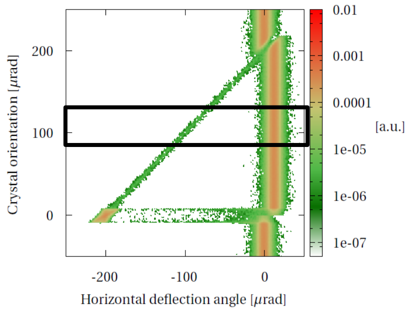




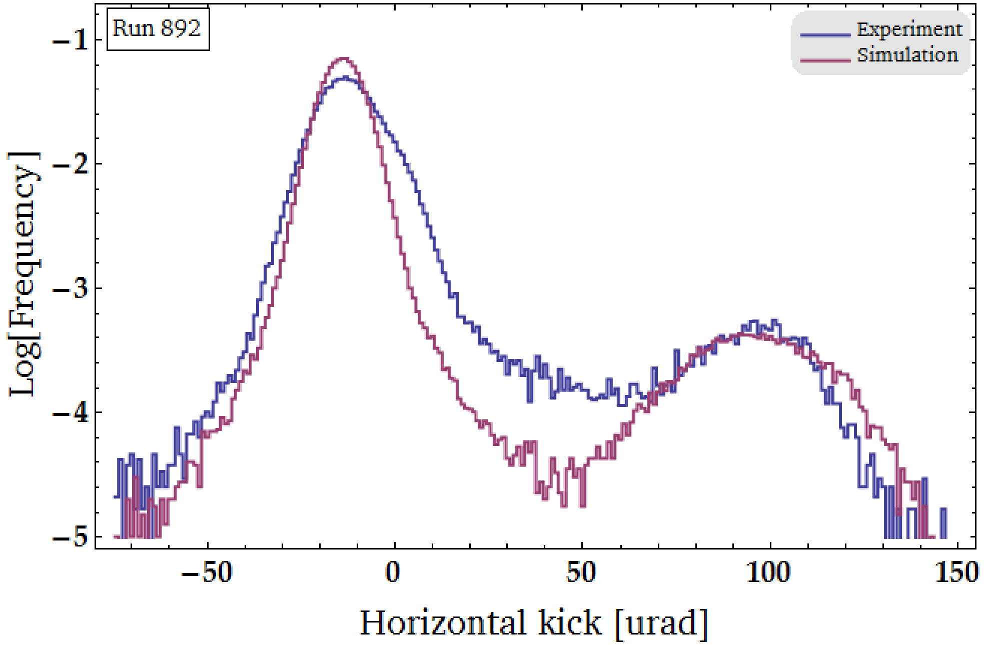


Results

- Volume reflection orientation



- SPS strip crystal (STF 50 – R.892)
  - (NB: Log scale to better appreciate VC)
  - Overall good agreement



Conclusions

- Semi-classical microscopic model of channeling
- Description of dechanneling, volume reflection and volume capture
  - Takes into account torsion and miscut
- Uses FLUKA interaction models

- Good agreement with results from UA9-H8 experiment
  - for the channeling peak description
  - for the dechanneling distribution
  - volume capture rate

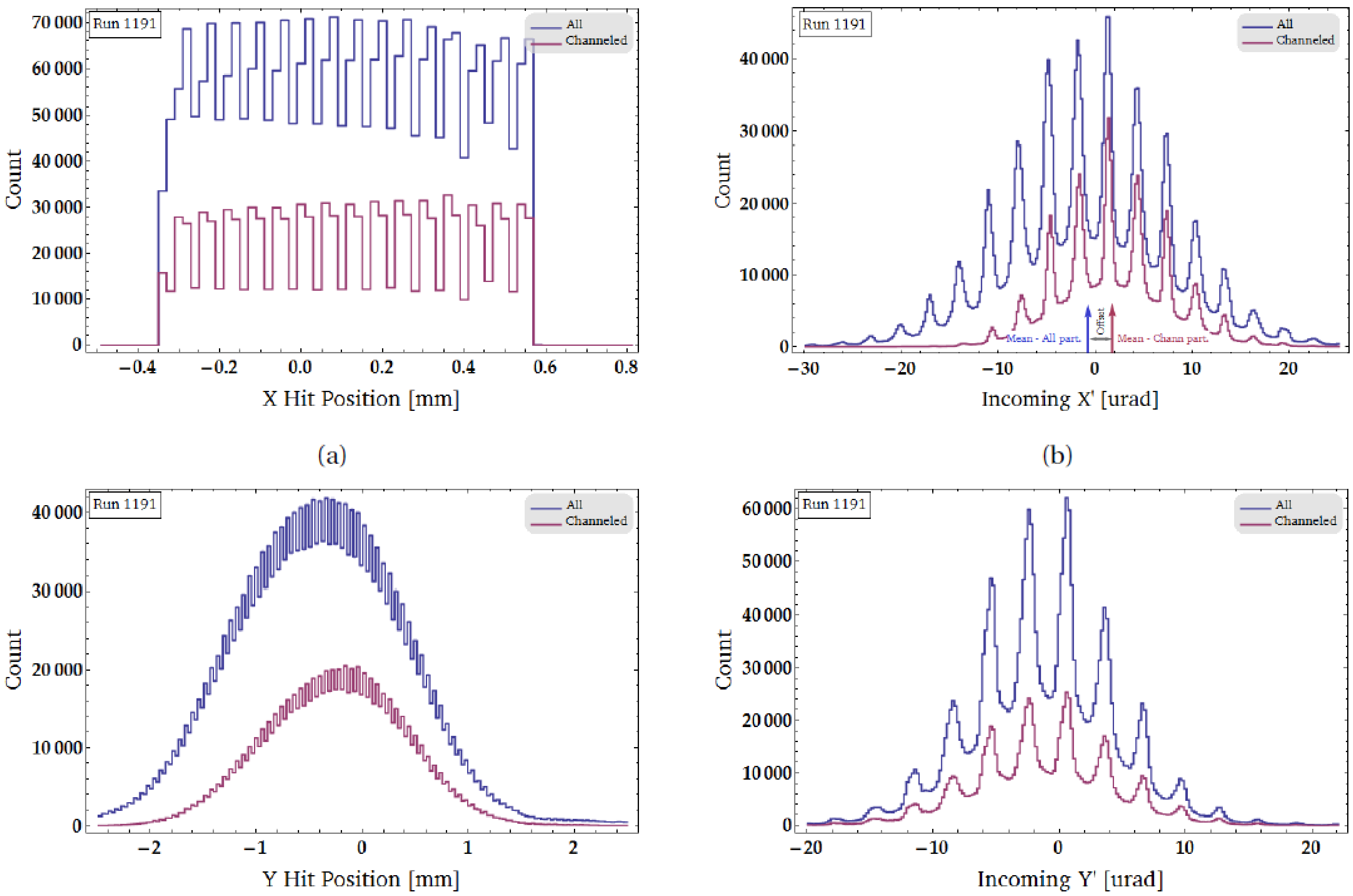
Acknowledgement to the UA9 collaboration !

- But :
  - Slight underestimation of the dechanneling rate
  - Exit kick determination still an open question

- In the future :
  - Finish implementation inside core FLUKA
  - EMD ? Altered ionization in channeling ?
  - Longer term : negatively charged particles, axial channeling,…

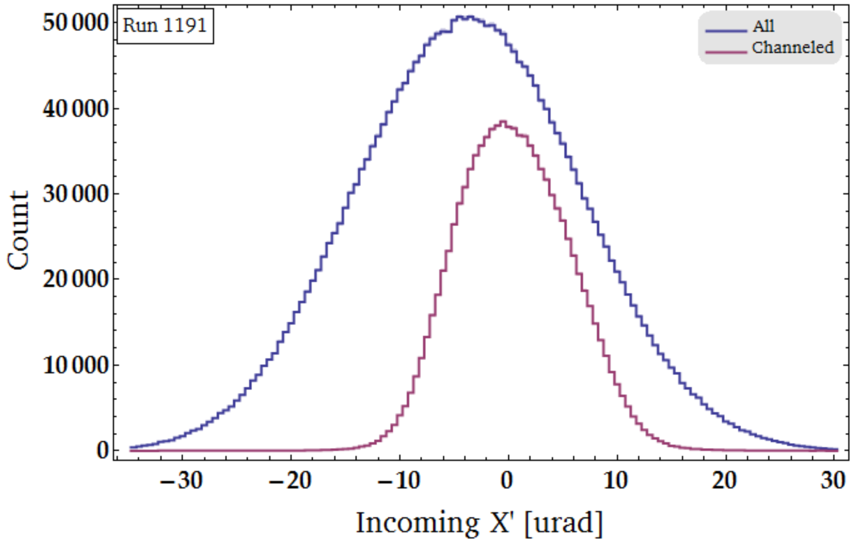
Thanks for your attention !

Backup


Run 1191
All
Channeled
Count
X Hit Position [mm]
(a)
Incoming X' [urad]
Mean - All part.
Offset
Mean - Chann part.
(b)
Y Hit Position [mm]
Incoming Y' [urad]

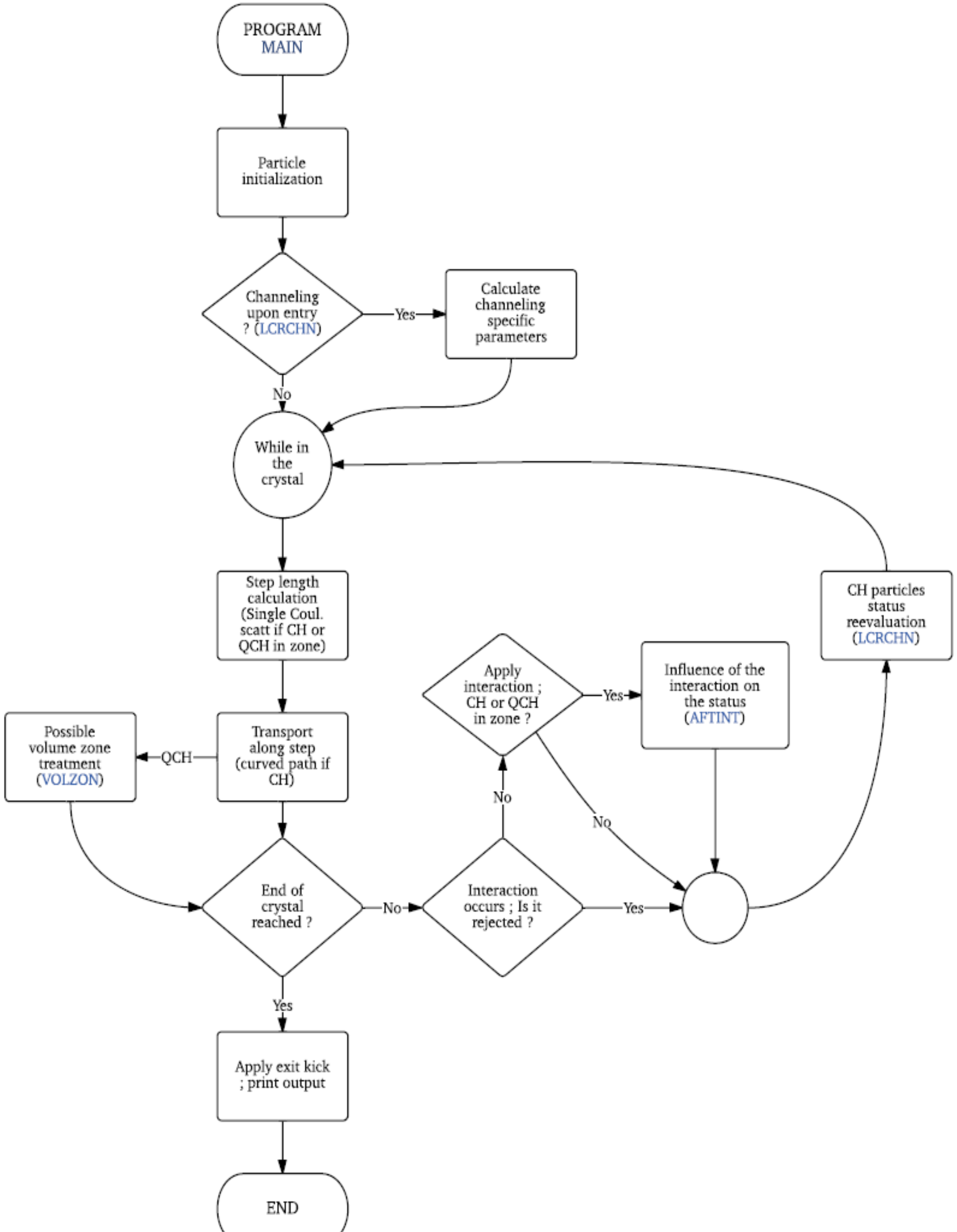
Backup

Run	Channeling Rate		Dechanneling Rate	
	Exp.	Sim.	Exp.	Sim.
608	29.04(15)	29.15(14)	3.31(6)	2.29(5)
630	25.12(10)	28.16(14)	8.05(7)	2.06(4)
889	29.04(6)	31.35(15)	3.65(2)	2.67(5)
899	24.99(3)	31.41(15)	14.7(1)	9.20(9)
1012	32.54(6)	37.06(15)	4.54(28)	2.27(5)
1028	36.87(6)	35.44(15)	9.96(39)	5.34(7)
1191	39.58(6)	37.03(15)	2.78(20)	2.80(5)
1240	50.73(3)	47.86(16)	3.49(22)	3.98(6)



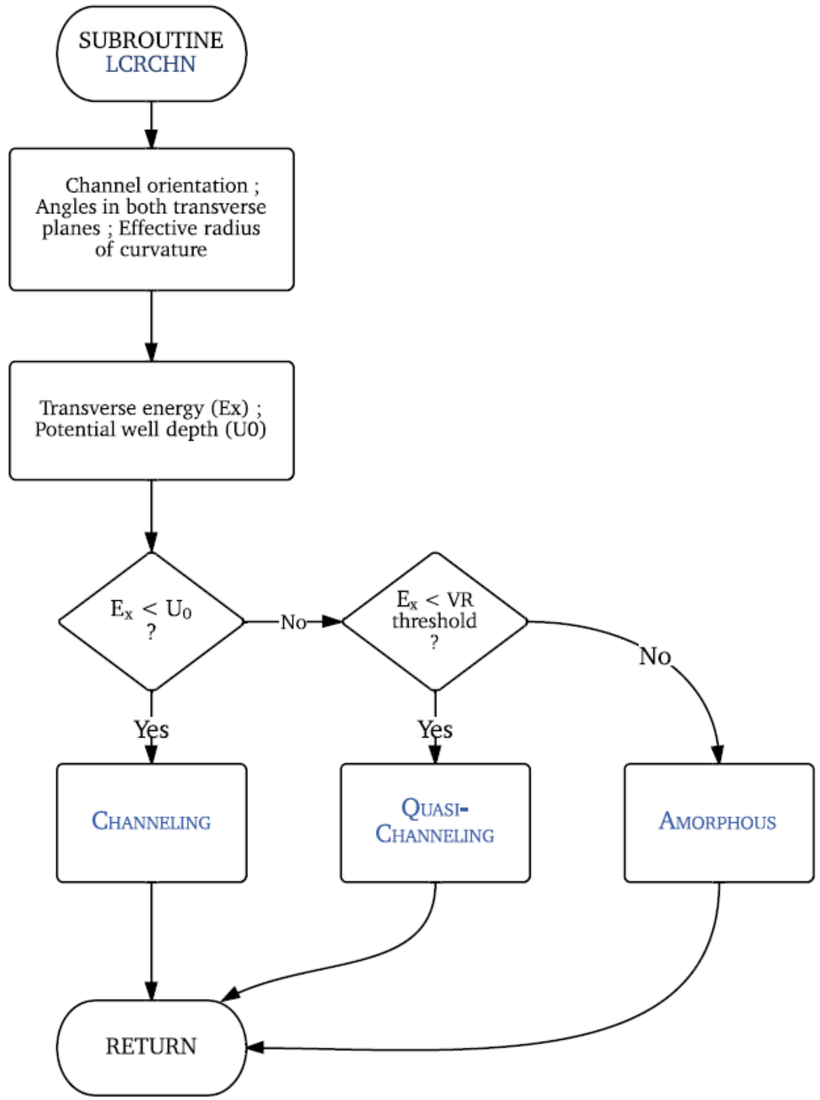
Run	Channeling peak				VR / AM peak			
	Experiment		Simulation		Experiment		Simulation	
	Mean	Sigma	Mean	Sigma	Mean	Sigma	Mean	Sigma
608	35.53(3)	7.27(2)	34.83(6)	10.17(4)	-1.06(3)	10.7(1)	-2.28(5)	13.58(4)
630	141.8(1)	11.3(1)	142.0(1)	10.68(4)	-1.96(3)	8.40(2)	-3.75(3)	8.09(2)
889	138.5(1)	9.26(2)	137.7(1)	10.63(4)	-8.23(2)	10.2(1)	-9.37(4)	9.32(3)
899	36.64(1)	7.38(1)	34.86(4)	9.97(4)	-5.15(1)	9.01(1)	-6.12(4)	10.7(1)
1012	50.83(2)	9.14(2)	50.82(6)	10.98(4)	-4.21(2)	9.00(1)	-3.18(4)	9.32(3)
1028	41.20(2)	7.01(1)	41.84(5)	9.79(4)	-4.16(2)	8.63(1)	-1.03(5)	11.7(1)
1191	61.26(2)	8.81(1)	60.18(6)	10.90(4)	-6.39(2)	9.97(1)	-3.32(4)	9.46(3)
1240	54.50(2)	8.55(1)	54.05(5)	10.56(3)	-5.61(2)	9.09(1)	-6.37(5)	10.6(1)

Backup

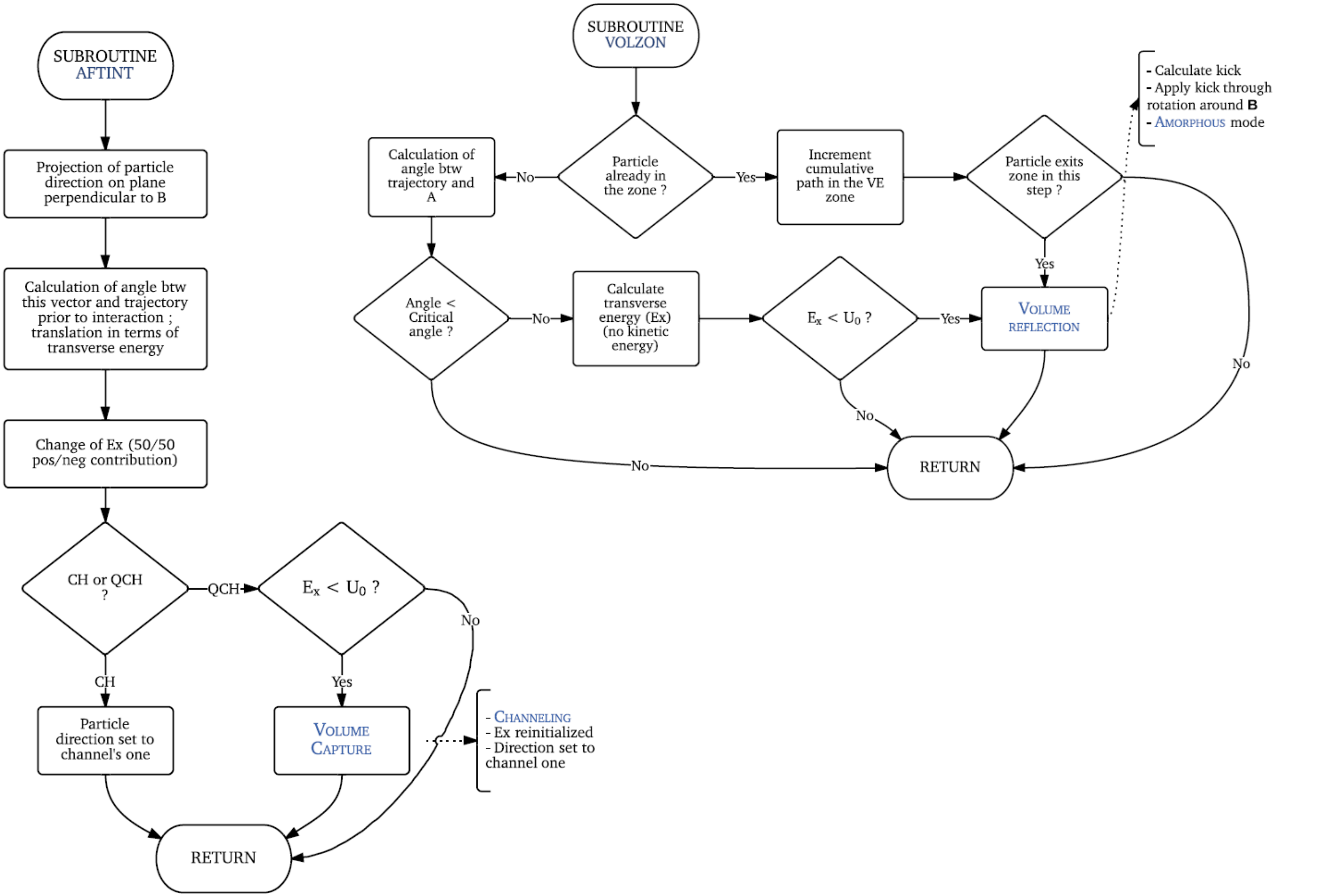


PROGRAM MAIN
Particle initialization
Channeling upon entry ? (LCRCHN)
Yes
Calculate channeling specific parameters
No
While in the crystal
Step length calculation (Single Coul. scatt if CH or QCH in zone)
Transport along step (curved path if CH)
QCH
Possible volume zone treatment (VOLZON)
End of crystal reached ?
No
Interaction occurs ; Is it rejected ?
Yes
No
Apply interaction ; CH or QCH in zone ?
Yes
Influence of the interaction on the status (AFTINT)
No
CH particles status reevaluation (LCRCHN)
Yes
Apply exit kick ; print output
END

Backup


SUBROUTINE
LCRCHN
Channel orientation ; Angles in both transverse planes ; Effective radius of curvature
Transverse energy (Ex) ; Potential well depth (U0)
$E_x < U_0$?
No
E_x < VR threshold ?
No
Yes
Yes
CHANNELING
QUASI-CHANNELING
AMORPHOUS
RETURN

Backup



SUBROUTINE AFTINT
Projection of particle direction on plane perpendicular to B
Calculation of angle btw this vector and trajectory prior to interaction ; translation in terms of transverse energy
Change of Ex (50/50 pos/neg contribution)
CH or QCH ?
QCH
CH
Ex < U0 ?
Yes
No
Particle direction set to channel's one
VOLUME CAPTURE
RETURN
- CHANNELING
- Ex reinitialized
- Direction set to channel one
SUBROUTINE VOLZON
Particle already in the zone ?
No
Yes
Calculation of angle btw trajectory and A
Increment cumulative path in the VE zone
Particle exits zone in this step ?
Angle < Critical angle ?
Calculate transverse energy (Ex) (no kinetic energy)
Ex < U0 ?
VOLUME REFLECTION
RETURN
- Calculate kick
- Apply kick through rotation around B
- AMORPHOUS mode