Recents developments of the FLUKA channeling model and benchmarking of LHC and SPS crystal-related activities

P. Schoofs, F. Velotti, P. Arrutia, L. Esposito, M. Fraser, B. Goddard, J-B. Potoine, R. Rossi , F. Salvat Pujol

Outline

FLUKA model of channeling

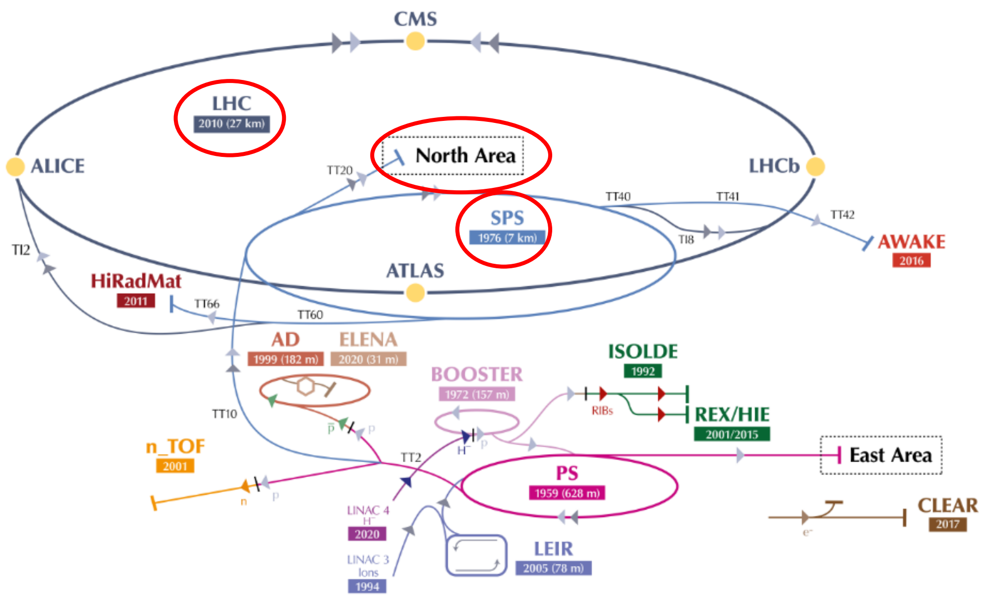
- CERN context of crystal-related activities
- Reminder of the model capabilities
- Recent development highlights:
  - Energy loss in Channeling regime
  - Microscopic tracking in quasi-channeling
  - Nuclear interaction alteration in quasi-channeling
- Future plans

Benchmark against LHC and SPS crystal-related activities

- Shadowing of the ES septum for SPS slow extraction
- LHC IR7 losses – Crystal collimation of ions

Conclusion

FLUKA model of crystal channeling – The context



- Inspired by development of crystal applications at CERN
- FLUKA = Monte Carlo code used for energy deposition studies at CERN
- FLUKA/SixTrack coupling for multi-turn studies

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

ELSEVIER

Monte Carlo modeling of crystal channeling at high energies

P. Schoofs [a,b,*], F. Cerutti [a], A. Ferrari [a], G. Smirnov [a]

[a] CERN, 1211 Geneva, Switzerland
[b] EPFL, 1015 Lausanne, Switzerland

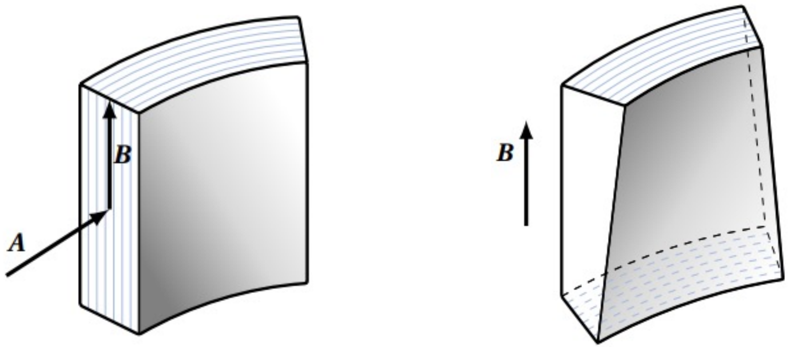
- Model presented first at Channeling 2012, Alghero
- Fully implemented into FLUKA in 2019-20
- Several key features added since then

Main concepts

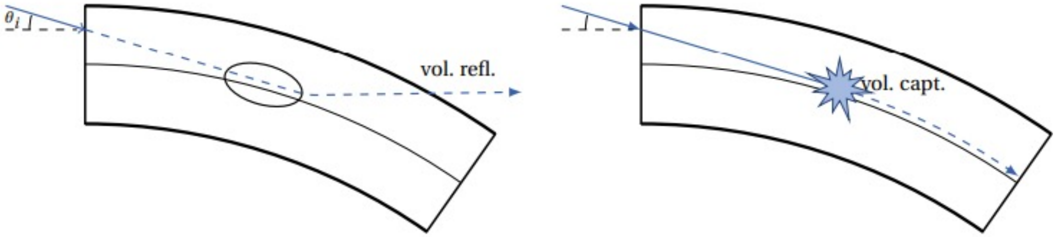
- Crystal tag applied to one or more regions of the geometry, enabling coherent effects

- Explicit parameters
  - Channel direction (+ normal)
  - Curvature
  - Torsion

- Based on entry conditions:
  - Channeling: particle follows crystal curvature, has altered interaction rates
  - Quasi-Channeling: particle is tracked in single scattering mode to assess its potential entry in volume zone (approaching tangency with the planes)
  - Amorphous: if conditions for CH or QCH are not respected, regular amorphous treatment of the particle



sign(θ_x)	Energy condition	Regime
−	$U_0 + pv\theta_b^2/2 < E_x$	Amorphous
−	$U_0 < E_x < U_0 + pv\theta_b^2/2$	Quasi-Channeling
−	$E_x < U_0$	Channeling
+	$E_x < U_0$	Channeling
+	$U_0 < E_x$	Amorphous



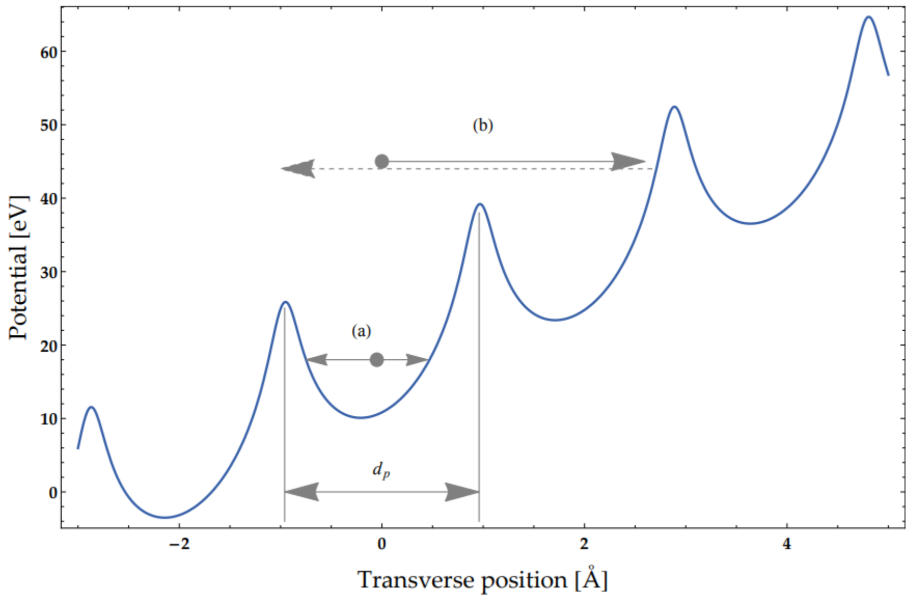
New developments

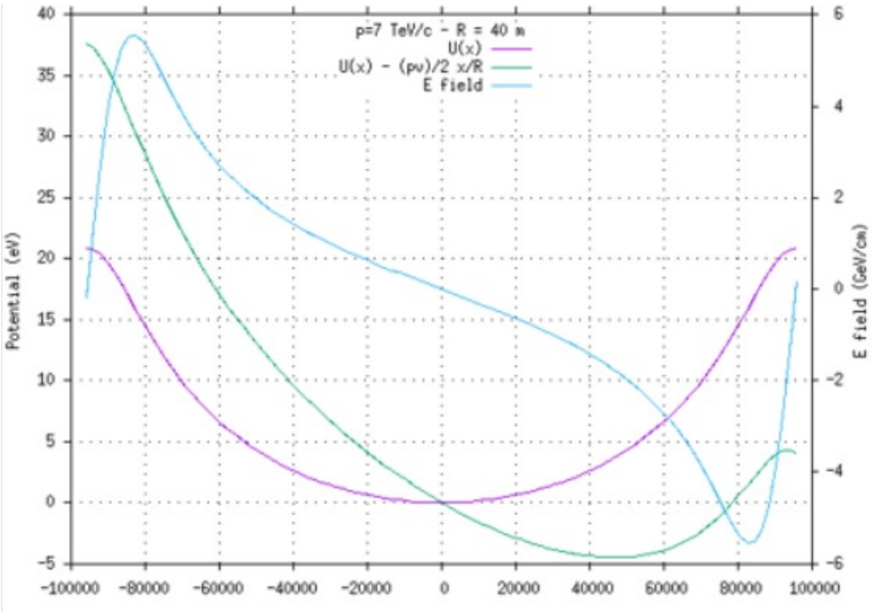
Tracking in quasi-channeling

New trajectory tracking in quasi-channeling.

« **Volume zone** » defined as the region where angle with channeling plane < θ_c

Inside the volume zone, tracking in the electric field of the local Lindhard's continuum potential





Distance from the center of the channel (fm)

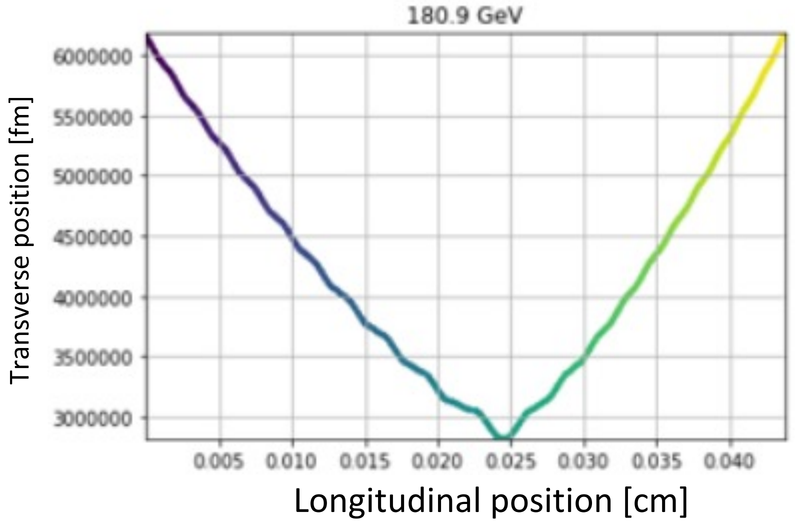
Moliere potential incl. centrifugal component is well known

We compute the corresponding E field at present location
Single scattering enabled → very short step (~15 um)

Said E field is applied to each step trajectory, modifying the end point

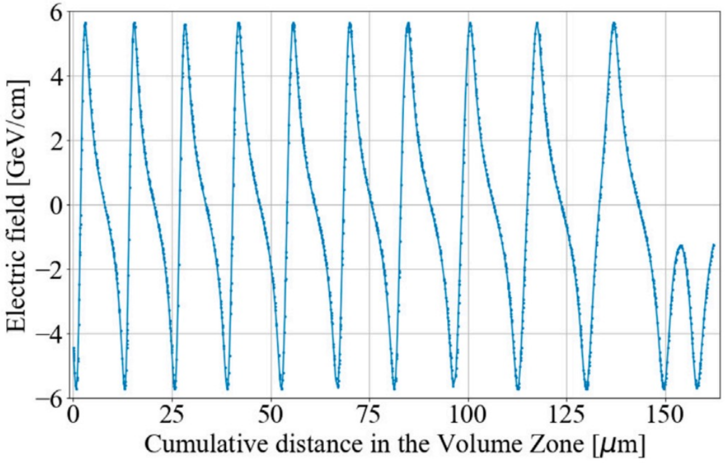
New developments
Tracking in quasi-channeling

- This naturally reproduces Volume reflection.
- Inside the volume zone, capture can also naturally occur in case of a scattering event reducing the energy of the transverse motion below the potential barrier
- In our tracking algorithm, the particle is then considered captured if it accomplishes 1.5 oscillations in the channel (-> channeled)



Capture rate ~2% for protons 180GeV

Investigations ongoing at very high energies



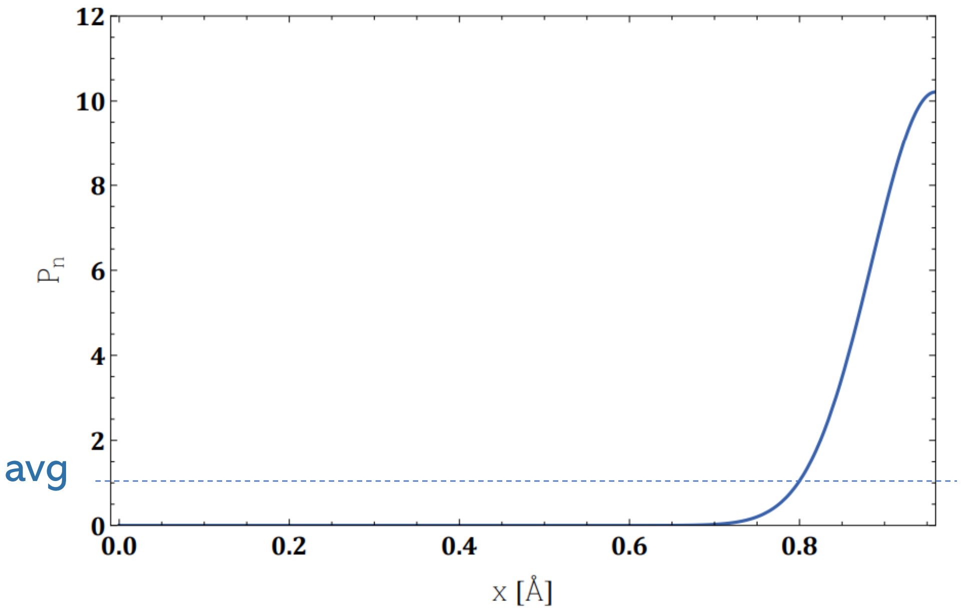
New developments
NI alteration in quasi-channeling

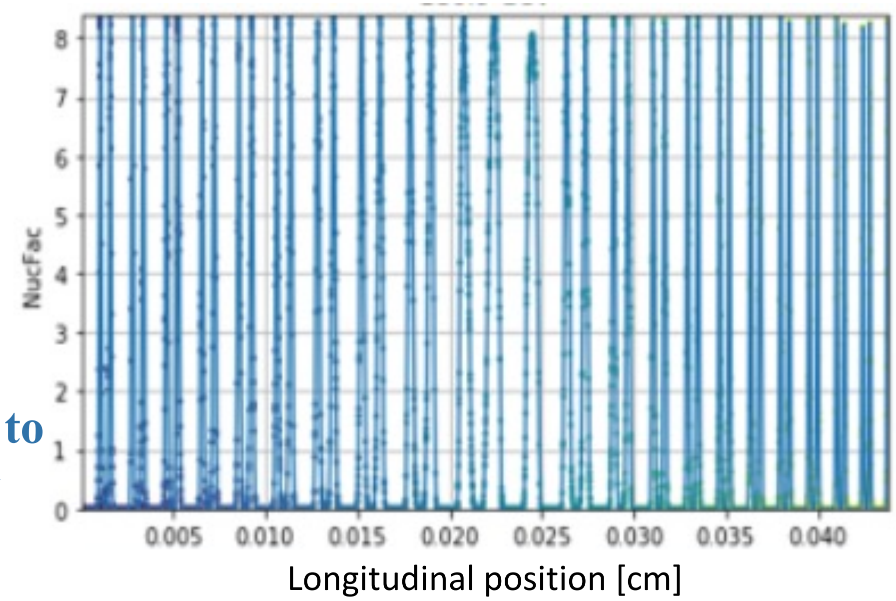
Microscopic tracking of quasi-channeled particles across crystal planes enables computation of NI alteration as for channeled ones

Density of nuclei across the channel (110)*

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

At each step, we compute the nuclear density factor
→ new interaction length and new step length





factor with respect to amorphous density

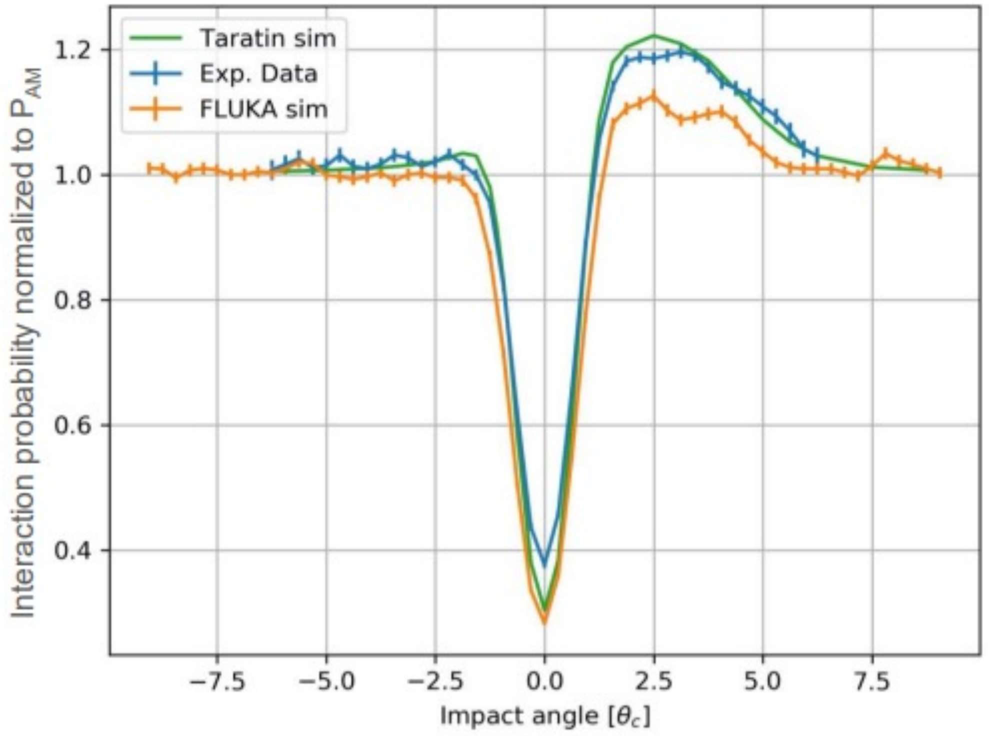
*W. Scandale, NIM B, **268** (2010), 2655

New developments
NI alteration in quasi-channeling

→Leads to increased NI rate for quasi-channeled, as expected from the experimental data

→Still the observed excess is not perfectly matching, and this is one of our ongoing efforts

Future tests include adjustments to where the volume zone starts and ends



A.M. Taratin's simulation from W. Scandale et al., Eur. Phys. J. C 80, 27 (2020)

New developments
Energy loss in channeling

Lindhard stopping power scaling at high velocities:

$$\frac{dE}{dx}(x_m) = \left(\frac{dE}{dx}\right)_{\text{am}} \underbrace{\left(\frac{1}{2} + \frac{Z(x_m)}{2Z}\right)}_{\chi}$$

Where x_m is the oscillation amplitude

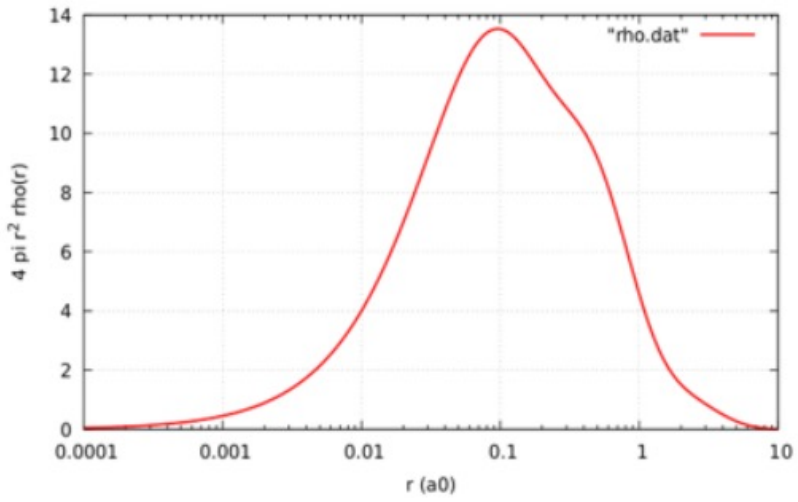
Very tedious to know $Z(x_m)$ (requires electron density at transverse position x_m).

Anisotropy so would require to treat other differential cross-section anisotropically as well. We wanted a solution that makes use of the pre-existing FLUKA model of energy loss → applying a factor

We looked for a different solution, one that makes use of a simplified model of electron density

→ Thomas-Fermi

Thomas-Fermi model

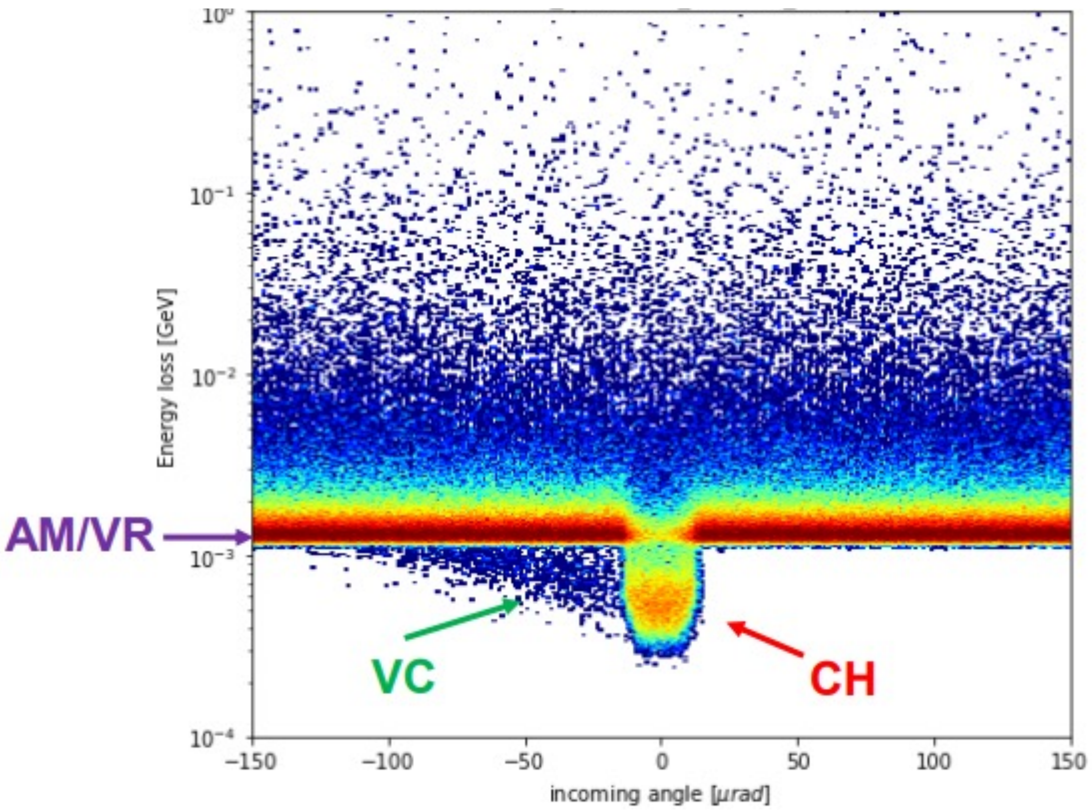


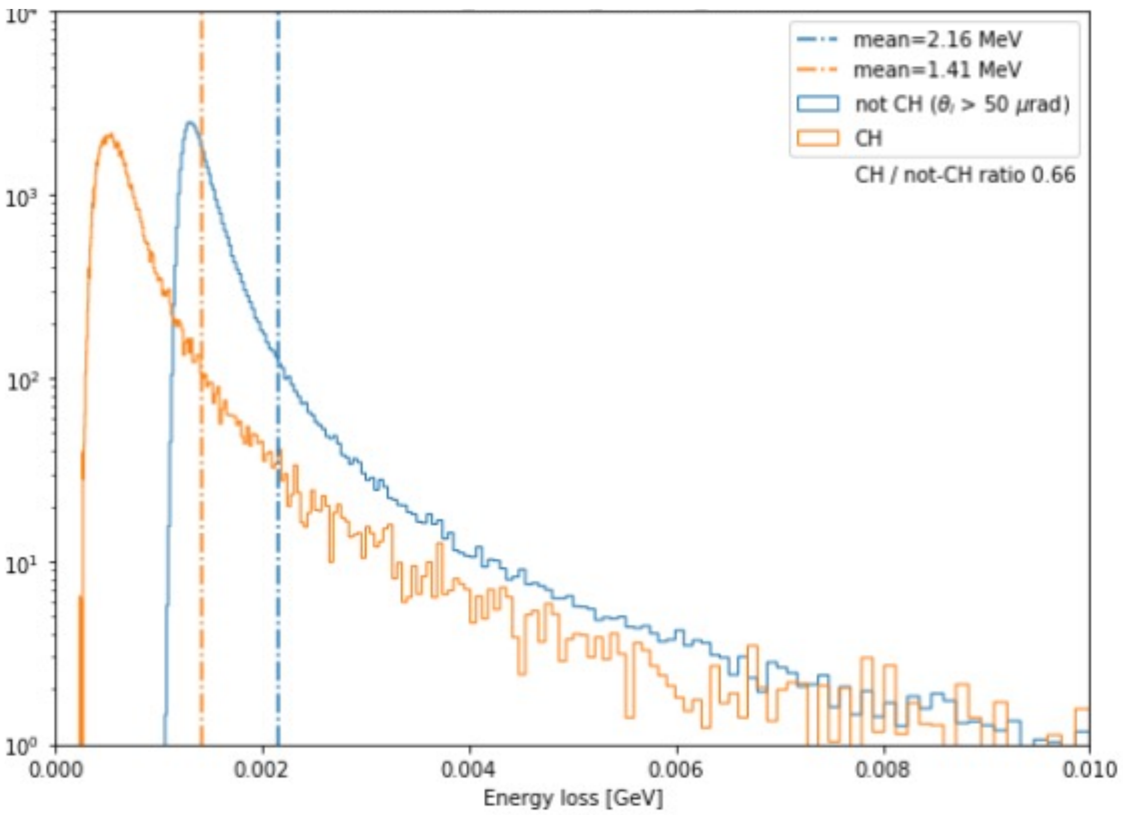
$$\chi = \frac{1}{2} + \frac{\int_{\frac{d_p}{2}-x_m}^{\frac{d_p}{2}+x_m} TF(x)\,dx}{2\int_0^{d_p} TF(x)\,dx}$$

Fraction of electron density enclosed by particle trajectory, inside $[\frac{d_p}{2} - x_m, \frac{d_p}{2} + x_m]$.

New developments
Energy loss in channeling

Case of 180 GeV/c protons on a 4mm-long strip crystal (150 urad bending)

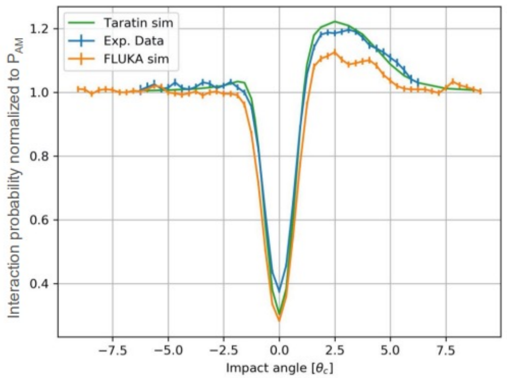


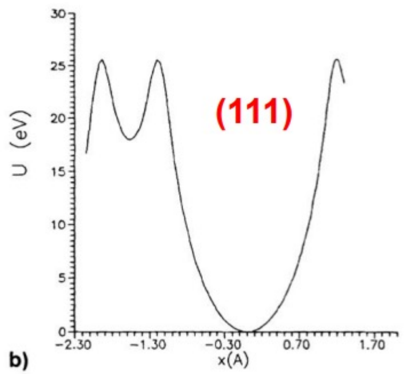


Future development plans

- Improve reproduction of nuclear interaction excess for quasi-channeled particles
- Understand the alteration of EMD for ion channeling
  (see W. Scandale et al., Phys Rev STAB 16 011001)
- Coherent effects for secondaries created in the crystal
- Refine planar channeling in (111) orientation
- Extend microscopic treatment to channeling
  - Natural reproduction of exit kick, dechanneling
- Miscellaneous refinements wrt volume effects zone, to improve capture/dechanneling rate at high energies

→ Opportunity in the context of FLUKA.CERN collaboration





frontiers in Physics
ORIGINAL RESEARCH
published: 27 January 2022
doi: 10.3389/fphy.2021.788253

New Capabilities of the FLUKA Multi-Purpose Code

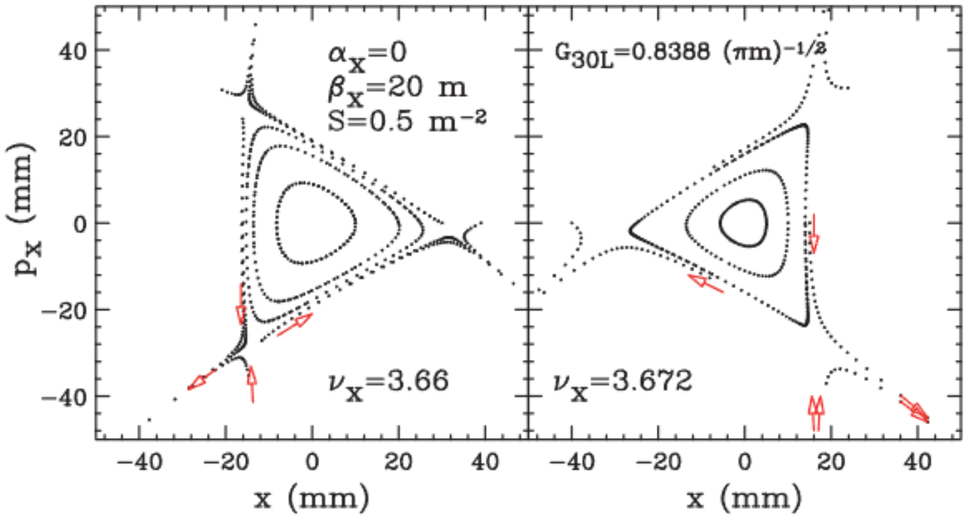
C. Ahdida[1], D. Bozzato[1,2], D. Calzolari[1], F. Cerutti[1*], N. Charitonidis[1], A. Cimmino[3], A. Coronetti[1,4], G. L. D'Alessandro[1], A. Donadon Servelle[1,5], L. S. Esposito[1], R. Froeschl[1],

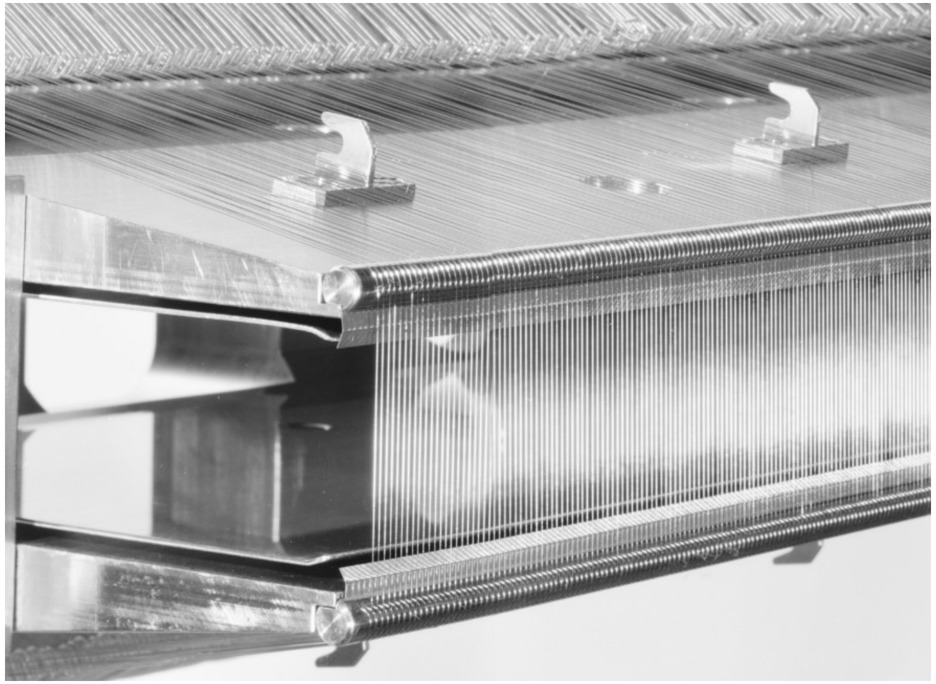
Applications

Shadowing of SPS slow extraction electrostatic septum

Electrostatic septum for slow extraction to North Area

Exploitation of third order resonance





Second worst activated area behind only the beam dump

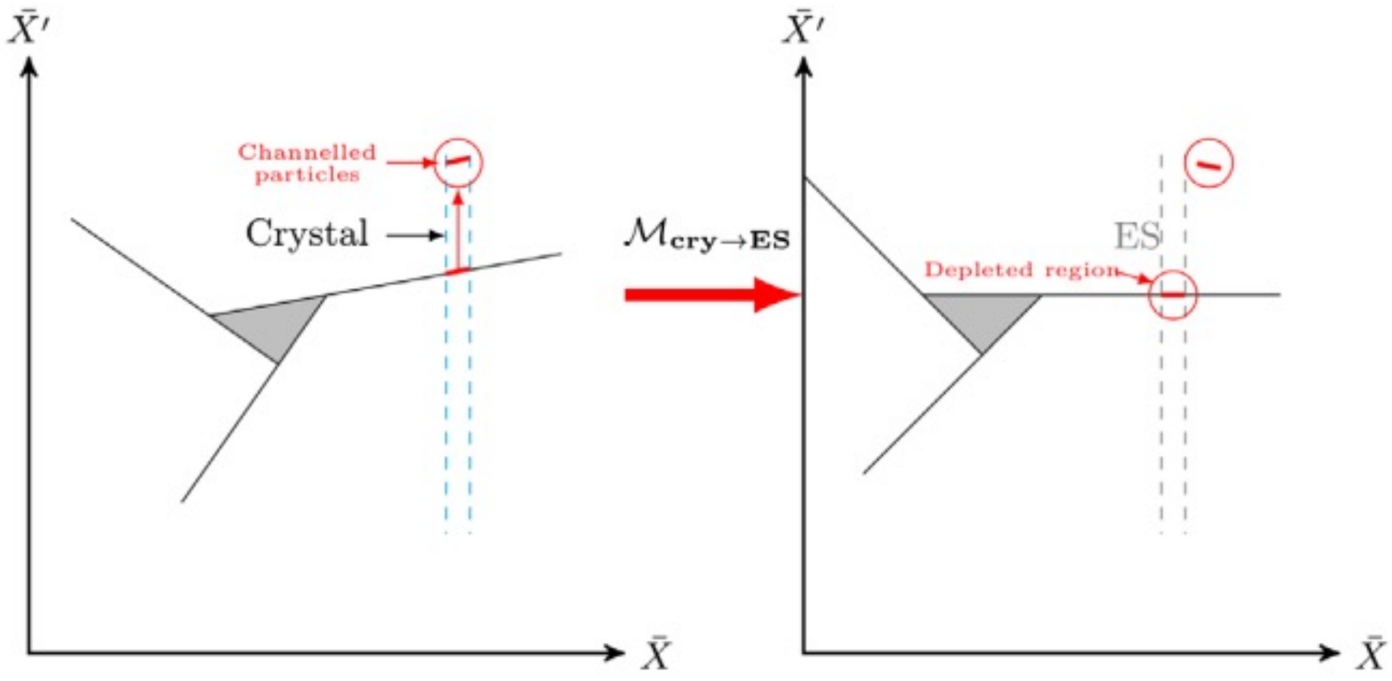
→Need of a solution to allow for increased intensity without going over radioprotection limits

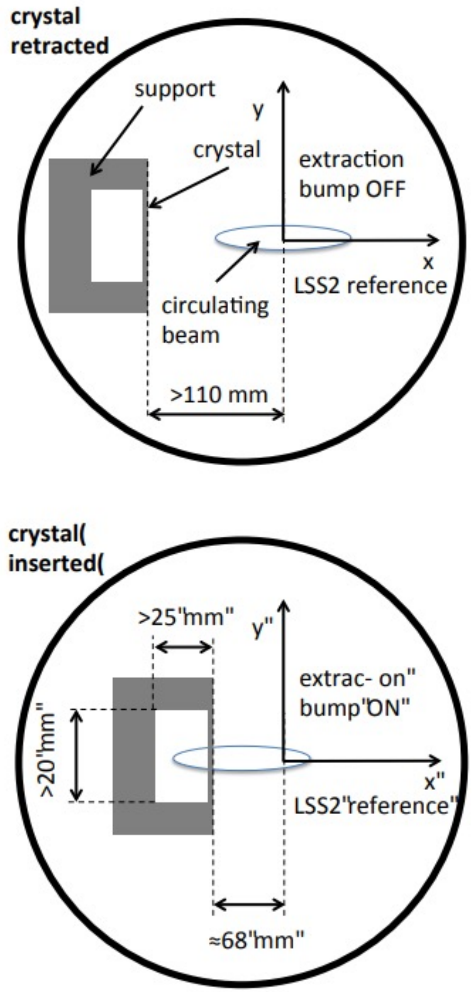
SHiP experiment in North Area : increase 4-fold in annual flux!

Applications
Shadowing of SPS slow extraction electrostatic septum

Thin crystal optimized for single-pass operation

<u>Crystal</u>: 2mm-long strip, 170 urad





F. Velotti et al., PRAB **22**, 093502 (2019)

Applications
Shadowing of SPS slow extraction electrostatic septum

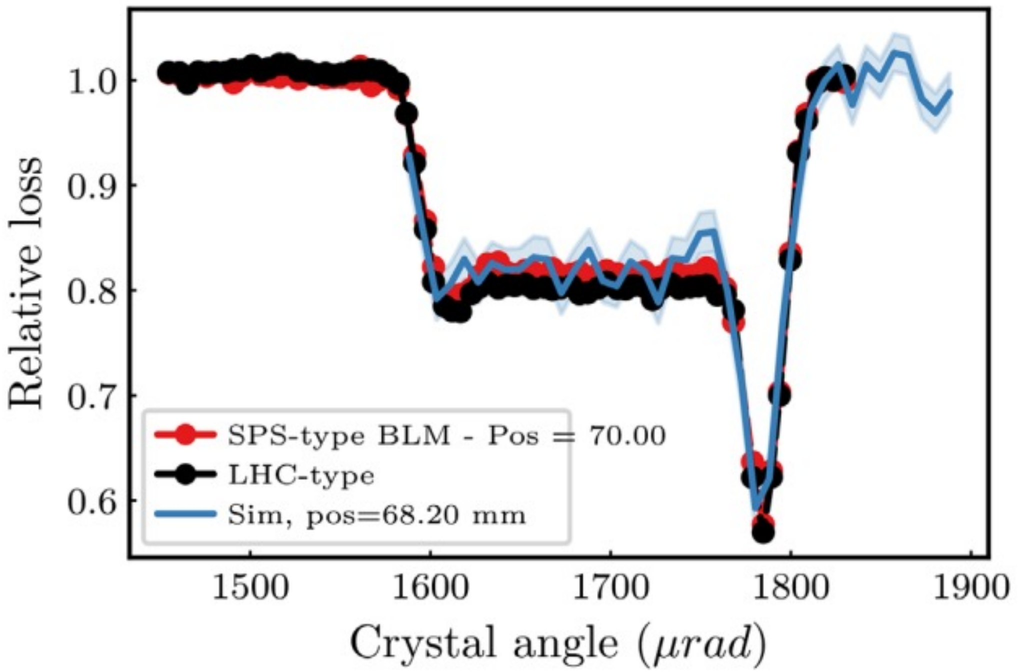
Particle interaction with crystal is simulated in FLUKA

Subsequent tracking in the beam line is done through *pycollimate* [2] and PTC

Results show a 40% decrease of the losses with the crystal in channeling **with high vulnerability to crystal misalignment**

Alternatively crystal in VR alignment → 20% less losses and a **much better resilience to crystal misalignment**

We note the excellent agreement between experiment and simulation



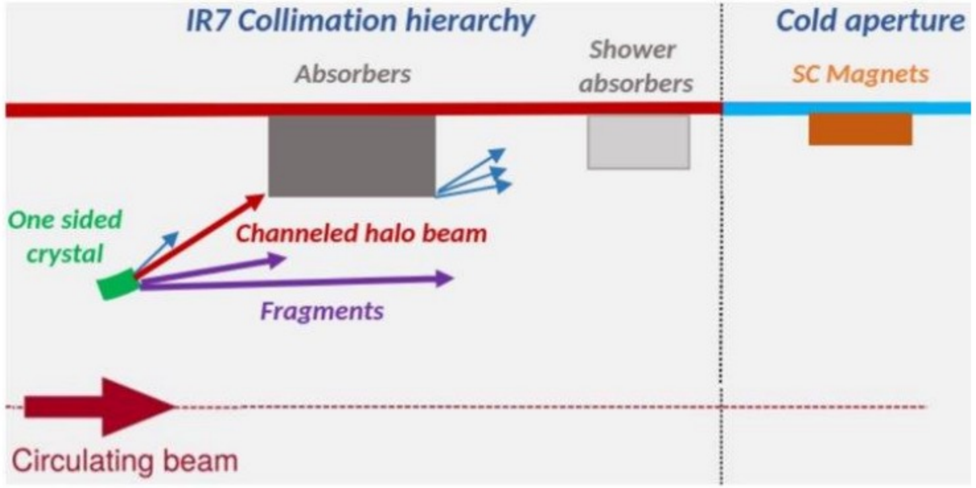
[2]: F. Velotti, PhD Thesis, CERN-THESIS-2017-041

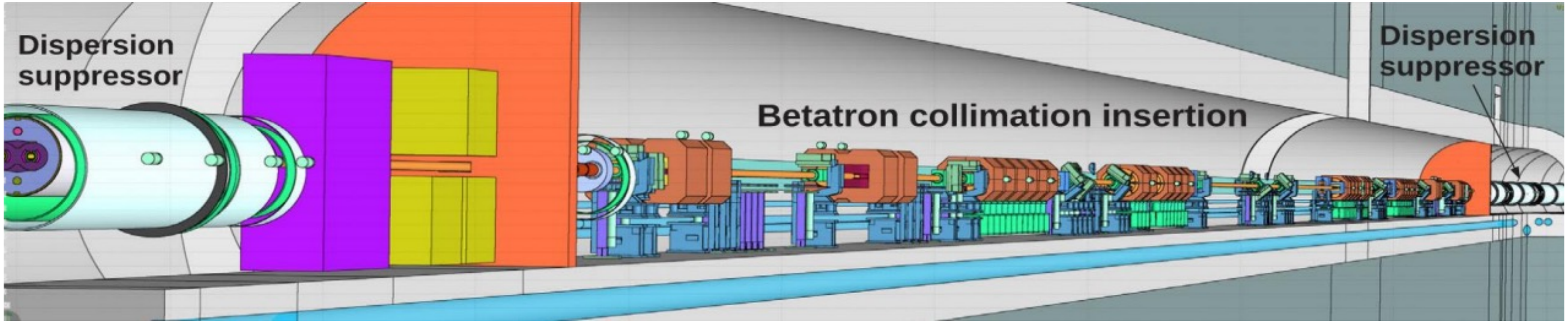
Applications

BLM response to the future HL-LHC crystal collimation in IR7

Crystal collimation is investigated for **ions** in HL-LHC

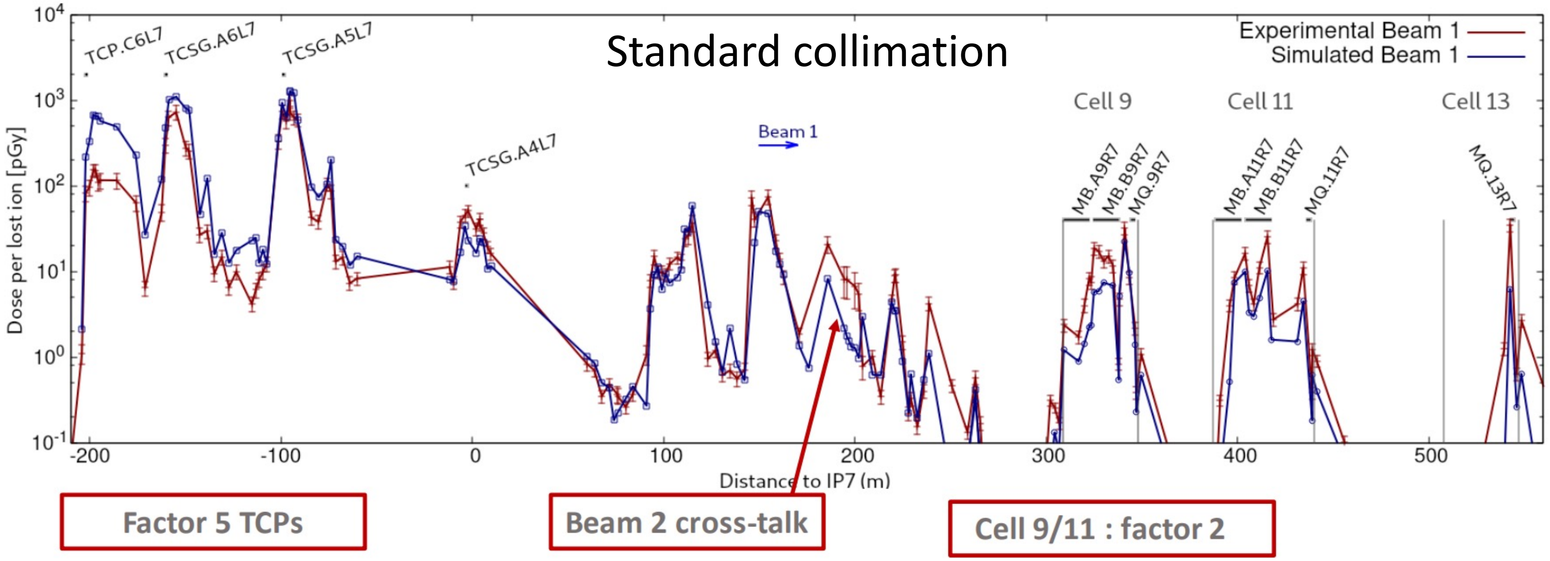
Simulations of collimation losses around the ring in that setup were conducted with FLUKA equipped with the channeling model, coupled with SixTrack for multi-turn tracking along the ring.

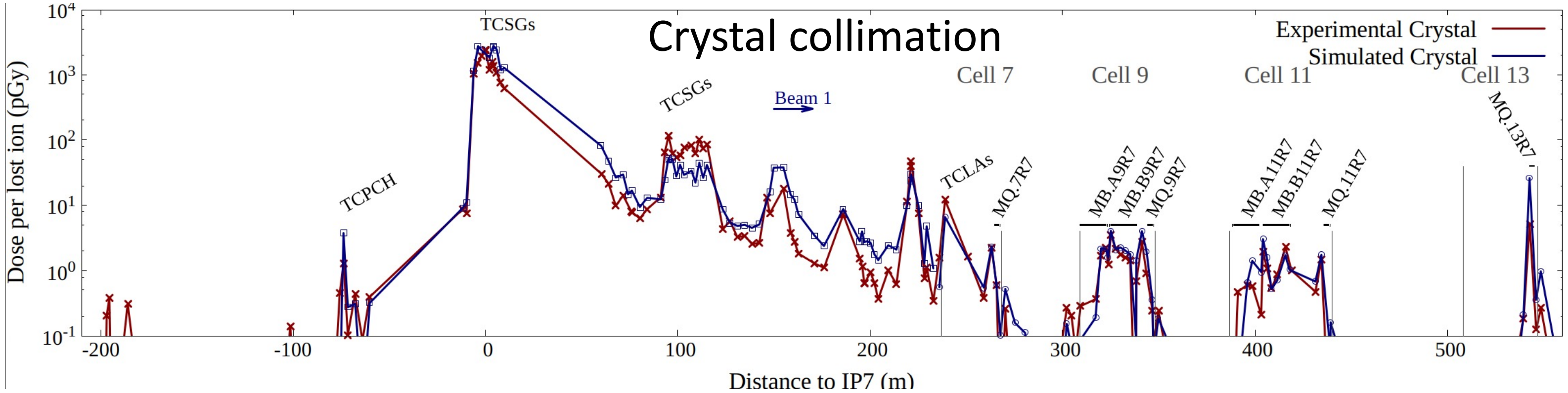




Applications

BLM response to future HL-LHC heavy ion crystal collimation in IR7





Each point corresponds to a dose measurement by one of the Beam Loss Monitors present close to the beamline.

Cold region (Dispersion suppressor) is situated after +200m from IP7.

BLM response is modelled in FLUKA, through reproduction of the device itself, and use of bespoke scorings that have been used and benchmarked extensively.

We note the good agreement between experiment and simulation of the losses due to the crystal collimation setup in IR7 for HL-LHC ions, and excellent agreement in the cold regions.

Conclusions

New features of the FLUKA model of channeling

- Energy loss in channeling
- Microscopic tracking in quasi-channeling
- NI rate in quasi-channeling

Still lots to come

- NI excess rate in quasi-channeling to be improved
- (111) planar channeling
- Refinements at high-energies

Two impressive results obtained benchmarking machine developement at CERN:

- Simulation of the loss reduction on the SPS ES septum
- Simulation of the crystal collimation losses as measured by BLM's

Acknowledgements

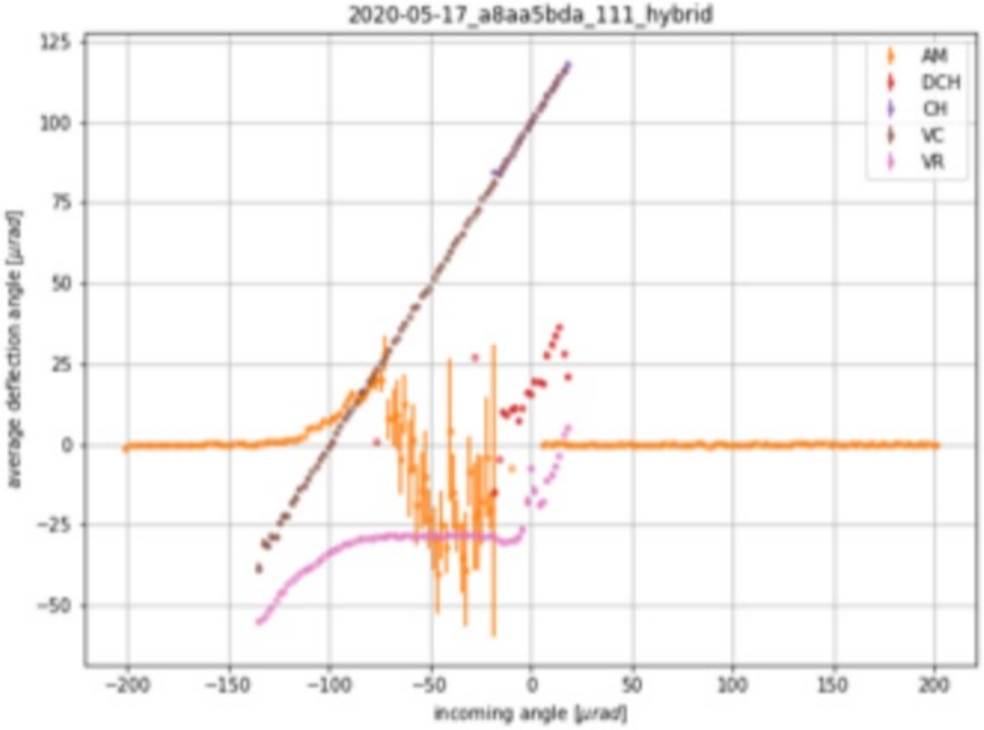
These crystal-related applications are only made possible through the work of a large number of people at CERN and collaborating institutes!

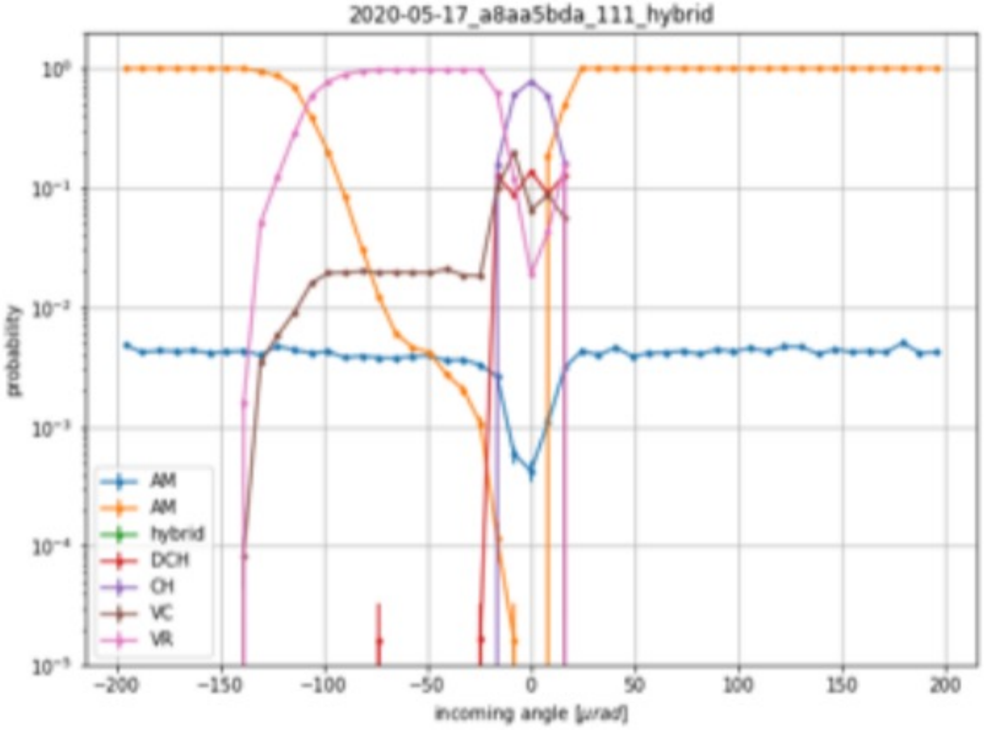
Thanks to all !

P. Bestmann, M. Butcher, M. Calviani, M. Di Castro, M. Donze, M. Fraser, S. Gilardoni, V. Kain, J. Lendaro, A. Masi, M. Pari, J. Prieto, W. Scandale, R. Seidenbinder, P. Serrano Galvez, L. Stoel, V. Zhovkovska, A. Afonin, Y. Chesnokov, A. Durun. V. Maisheev, Y. Sandomirskiy, A. Yanovich, F. Galluccio, F. Addesa, J. Borg, G. Hall, T. James, M. Garattini, M. Pesaresi, A. Kovalenko, A. Taratin, A. Natochii, A. Denisov, Y. Gavrikov, Y. Ivanov, M. Koznov, L. Malyarenko, V. Skorobogatov, R. Bruce, R. Cai, F. Cerutti, M. D'Andrea, P. Hermes, A. Lechner, D. Mirarchi, S. Redaelli, V. Rodin, A. Waets and F. Wrobel

Thank you for your attention !

Appendix : results of VZ tracking





Energy loss

Integrals

- We consider one atom at either channel wall and examine the fraction of electronic density enclosed by a trajectory with oscillation amplitude x_m:

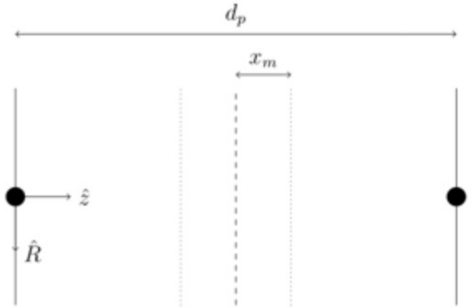


Figure 5: Cylindrical coordinates used to integrate the electron density from the first wall. The dot represents the nucleus: the electron density extends well into the channel.

- Explicitly, the integrals (conveniently done in cylindrical coordinates) are:

$$\chi(x_m) = \frac{1}{2} + \frac{1}{2Z_{d_p}} \left\{ \int_0^{2\pi} \mathrm{d}\varphi \int_{z_1}^{z_2} \mathrm{d}z \int_0^{\sqrt{z_2^2 - z^2}} \mathrm{d}R\, R\, \rho(\sqrt{R^2 + z^2}) + \int_0^{2\pi} \mathrm{d}\varphi \int_{z_1}^{z_2} \mathrm{d}z \int_0^{\sqrt{z_2^2 - z^2}} \mathrm{d}R\, R\, \rho[\sqrt{R^2 + (d_p - z)^2}] \right\}$$

$$Z_{d_p} = 2\pi \int_0^{d_p} \mathrm{d}z \int_0^{\sqrt{d_p^2 - z^2}} \mathrm{d}R\, R\, \rho(\sqrt{R^2 + z^2})$$

Energy loss

Final formulae

- The integral is analytical. With z_1=d_p-x_m and z_2=d_p+z_m we have:

$$\chi(x_m) = \frac{1}{2} + \frac{Z}{Z_{d_p}}\frac{1}{4}\sum_{i=1}^{3} a_i \frac{1}{b_i}\left[\frac{1}{b_i}(\mathrm{e}^{-b_i z_1/b} - \mathrm{e}^{-b_i z_2/b}) - \mathrm{e}^{-b_i z_2/b}(z_2 - z_1)\right]$$

$$Z_{d_p} = \frac{Z}{2b^2}\sum_{i=1}^{3} a_i \left[\frac{b^2}{b_i^2}\left(1 - \mathrm{e}^{-b_i d_p/b}\right) - \frac{b}{b_i} d_p \mathrm{e}^{-b_i d_p/b}\right]$$

- Core subroutines affected:

dedx.f: `IF ( KCHNNL .EQ. 2 ) DEDX = CHDEDX * DEDX`

deltar.f: `IF ( KCHNNL .EQ. 2 ) TE = CHDEDX * TE`