H8 crystal data analysis

22/08/2014 – Collimation Upgrade Meeting

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The UA9 collaboration is studying techniques to steer ultra-relativistic beams with bent crystals to improve the collimation of proton and heavy ion beams at the LHC. Measurements of key crystals properties (bending angle, channeling efficiency, etc.) are performed on the SPS extraction line (H8) with 400 GeV/c protons before testing crystals with circulating beams.

Scope of my master thesis work:
Consistently analyze all the crystals tested in H8 (total of 15 between 2009-2012).
- Compile a comprehensive statistical treatment of different crystals
- Identify “fine” systematic effects (e.g., transitions)
- provide inputs to crystal code developers

Immediate goal: compile list of experimental data for an upcoming workshop on crystal simulations.
H8 experimental Layout

- Five silicon micro-strip sensors (active area 3.8x3.8 cm² in the x-y plane) are used to track the particles in the plane orthogonal to the beam direction before and after passing through the crystal.
- High precision goniometer is used to modify the crystal plane orientation with respect to the beam direction.
Two kind of crystals were test in H8

- **Strip crystal**: the anticlastic bending is induced on the planes (110)
- **Quasi-mosaic crystal**: the anticlastic bending is induced on the planes (111)

The main difference is that the strip channels have all the same width, while the QM have a main channel and a smaller secondary (1/3).

A total of 10 crystals were analyzed, 7 strip and 3 quasi-mosaic
Run Analysis

We developed analysis tools in Root to get from the raw data (details in next slides):

- **Alignment run ->**
  - check of beam parameters (e.g. input distributions on crystal)
  - telescope resolution

- **Hi stat CH ->**
  - Geometrical cut (different strategy between ST and QM)
  - Torsion correction
  - Crystal channeling efficiency
  - Dechanneling length
  - First look to transition region
  - Population studies (Future paper)

- **Angular scan run ->**
  - Volume capture features

The analysis for the **STF45** crystal is used as reference case for comparison with crystal simulation routines

Complete analysis is presented in the previous meeting **CoLUSM #38**
The optimum channeling condition is the one studied in more detail.

All the analysis are performed by studying the deflection $x$ angle as a function of the impact $x$ angle. We can then distinguish three regions with respect to the $x$ deflection:

- **Channeling**, the spot around 150 $\mu$rad
- **Transition region** between the amorphous and the volume reflection zone
- **Dechanneling**, the region between the first two
The channeling efficiency is evaluated at two different angular cuts $\pm 5\,\text{e}\pm 10\,\mu\text{rad}$, that for 400 GeV/c protons represent the critical angle for channeling and two times the critical angle, respectively.

Projecting on the y axis the kick, with the cut described, are obtained.

$$\eta = 0.69 @ \pm 5\,\mu\text{rad}$$

$$\eta = 0.53 @ \pm 10\,\mu\text{rad}$$

Channeling Efficiency
Dechannelling length

On the same histogram the **dechannelling length** analysis is also performed

This is a key parameter to improve simulations.

The dechannelling probability is described as an exponential decay as a function of the kick angle, the characteristic dechannelling length is calculated from an exponential fit in the dechannelling region.

± 5 µrad  
± 10 µrad

22/08/14
Dechanneling length

Dechanneling Length

± 5 μrad

The exponential fit gives the dechanneling angle.
To get the dechanneling length we have to multiply the parameter by the bending radius of the crystal.
Variation on the fit range don’t show significant changes of the dech length, that is estimated to be ~ 1,4 mm
Deflection analysis

With different selection of impact angle we are able to study the different kind of interaction of particle with a bent crystal.

- Channeling deflection angle
- Volume reflection angle
- Amourphous angle

The same gaussian fit gives also t

VR – [20,30] μrad

AM – [-30,-20] μrad

± 5 μrad

± 10 μrad
Deflection analysis

The same gaussian fit gives also the sigma distribution value

CH - ± 5 μrad
Mean 144.0 ± 0.1 μrad
Sigma 7.18 ± 0.04 μrad

CH - ± 10 μrad
Mean 143.08 ± 0.1 μrad
Sigma 8.21 ± 0.04 μrad

VR – [20,30] μrad
Mean -14.03 ± 0.12 μrad
Sigma 8.03 ± 0.11 μrad

AM – [-30,-20] μrad
Mean 0.01 ± 0.18 μrad
Sigma 7.31 ± 0.15 μrad
The channeling peak position are studied as a function of impact angle.
Also the distribution sigma is plotted as a function of impact angle.
The **transition zone** describes how the amorphous region is transformed to the volume reflection region after the channeling region.

The trend of the peak plotted would be useful for a confrontation with the crystal simulation routines.

**Peak position in transition zone**

**Sigma peak in transition zone**
The Population of the three different regions are evaluated as a function of the impact incoming angle.
Angular Scan Analysis

The angular scan has the same geometrical cuts and torsion correction. The deflection $x$ as a function of the impact $x$ angle is shown.

In this case we can see all the volume reflection region, and the halo that have the same trend of the channeling spot is the volume capture region.
A first try for a description is under investigation: in this region are present both volume capture and dechanneling.

As described in [2] the fraction of channeled particle is

\[ f(z) \propto \cos \theta \exp \left(-\frac{z}{L_D}\right) \]

So, if we perform an exponential fit in the rising zone we can obtain a characteristic length which should be proportional to \( L_D \).

This length can be obtained as

\[ L_C = R \cdot (\alpha_{bend} - \theta^*) \]

where \( \theta^* \) is the fit parameter.

This length is estimated to be \( \sim 1.1 \text{ mm} \).

The same analysis on the STF50 and on STF38 give nearly the same results.

A webpage is ready, and will be soon on line. It contains the necessary input to reproduce the experimental data of the reference case.

Crystal Collimation

H8 Single Pass Test Data Analysis

Inputs for Simulation Routines

Scope

Requirements for comparison

Inputs

Reference case, STE45

Complete list of crystal and beam parameters

The results of the comparison will be discussed in the upcoming Crystal Channeling Workshop.
Conclusion

Achieved goals:

✓ A complete analysis of the crystal tested in the H8 line has been done.
✓ The results of the present analysis fit the results in literature.
✓ Many fine systematic effect were analyzed for the first time.
✓ A complete list of experimental data and inputs are ready for crystal code developers.

Future goals:

☑ understanding and development of an analytical model of the “fine” effects observed.
☑ implementation of the analytical models to improve the crystal simulation routines.
BACKUP
Track reconstruction

- Only one track per event is reconstructed.
- The event reconstruction uses the first two and the last two detectors to measure the incoming and the outgoing angle of the tracks, respectively.
- The impact point at the crystal position is given by the interpolation of the incoming and the outgoing tracks.
A complete experimental characterization of a crystal consists of different acquisition runs

- **“Alignment”** run: used to validate the telescope performance without crystals on the beam line
- **Transverse position scan**: used to find the crystal, when it crosses the beam
- **Crystal angular scan**: used to identify the interesting angular regions - amorphous, channeling and volume reflection orientations.
- **High statistic acquisitions**: performed in the region where we want fully analyze a given effect. Typically, done in the optimum channeling orientation.
With the crystal removed from the line is possible to measure the key parameters:

- Beam divergence
- Beam distribution
- Telescope resolution
Alignment Run Analysis

The incoming beam spot can be well approximated by a double Gaussian (see next slide).

The surrounding background (square area in light blue) is given by the interaction of the beam particle with the micro collimators placed at the beginning of the line;

When the micro collimators are moved the shape of the background change.
Alignment Run Analysis

Here we can see the beam profile in the orthogonal plane.

Double Gaussian shape of the beam core

x sigma of 0.96 mm
y sigma 0.72 mm

The asymmetric tail are not fitted, because are the background due to the micro collimators.
Alignment Run Analysis

The beam divergence is found to be 10.67 μrad in x and 7.66 μrad in y.

This characteristics are crucial for the key measurements.

The input angular distributions are bigger than θ_c we need to apply a selection to analyze the different effects.
Alignment Run Analysis

This plot shows the difference between the outgoing and the incoming angle of the tracks without any object on the beam line.

The sigma of this distribution gives us the telescope resolution taking into account a variety of systematic effects, including scattering in air.

The resolution of the telescope is 5.7 μrad in good agreement with the resolution estimated in [1].

[1] M. Pesaresi et al., Design and performance of a high rate, high angular resolution beam telescope used for crystal channeling studies, 2011 JINST 6 P040006
### Alignment Run Recap

Each crystal has a good alignment run. If a run is missing, the closer one is used.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>STF38</td>
<td>1.014</td>
<td>0.721</td>
<td>10.670</td>
<td>7.658</td>
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</tr>
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<td>5.731</td>
</tr>
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<td>0.949</td>
<td>11.730</td>
<td>8.964</td>
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</tr>
<tr>
<td>STF48</td>
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<td>0.960</td>
<td>11.880</td>
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<tr>
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<td>10.880</td>
<td>8.022</td>
<td>5.496</td>
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<tr>
<td>STF70</td>
<td>1.239</td>
<td>0.827</td>
<td>9.216</td>
<td>5.748</td>
<td>5.284</td>
</tr>
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<td>STF71</td>
<td>1.215</td>
<td>0.825</td>
<td>9.111</td>
<td>5.731</td>
<td>5.311</td>
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<td>QMP26</td>
<td>1.269</td>
<td>0.821</td>
<td>9.134</td>
<td>5.774</td>
<td>5.421</td>
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<td>QMP28</td>
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<td>0.822</td>
<td>9.153</td>
<td>5.770</td>
<td>5.408</td>
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<td>QMP29</td>
<td>1.239</td>
<td>0.827</td>
<td>9.216</td>
<td>5.748</td>
<td>5.284</td>
</tr>
</tbody>
</table>
Two kinds of cuts are performed on the initial distributions

**Geometrical cut**

- The geometrical cuts are used to select particle impinging on the crystals and can be established by looking at the spread given by the multiple coulomb scattering.

**Angular cut**

- The angular cuts are performed to study the coherent interactions in crystals.
Geometrical cut

Deflection vs d0x nocut

Entries: 824848
Mean x: -0.08454
Mean y: 5.818
RMS x: 1.15
RMS y: 30.75

Deflection vs d0y nocut

Entries: 824848
Mean x: 0.06239
Mean y: 0.453
RMS x: 0.878
RMS y: 6.586

Cut -> [-0.1;0.2] mm
Example of QM

The crystal face xy is not flat, because of a characteristic additional bending on the QM crystal

– the kick as a function of the impact position (on a fixed crystal) shows a behavior similar to an angular scan.

We have to find a region where this curvature is negligible.
The table summarizes the geometrical cuts made.

<table>
<thead>
<tr>
<th>Xtal</th>
<th>X min [mm]</th>
<th>X max [mm]</th>
<th>Y min [mm]</th>
<th>Y max [mm]</th>
<th>Initial gonio angle [μrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF38</td>
<td>-1.05</td>
<td>-0.05</td>
<td>-2.033</td>
<td>2.29</td>
<td>4712400</td>
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<td>STF45</td>
<td>-0.10</td>
<td>0.20</td>
<td>-2.07</td>
<td>2.28</td>
<td>4714800</td>
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<td>QMP27</td>
<td>-0.40</td>
<td>0.00</td>
<td>-1.50</td>
<td>1.50</td>
<td></td>
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<tr>
<td>STF47</td>
<td>-0.90</td>
<td>1.10</td>
<td>-2.83</td>
<td>2.86</td>
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<td>-0.70</td>
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<td>4712947</td>
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<td>-0.15</td>
<td>0.40</td>
<td>-2.91</td>
<td>2.96</td>
<td>4714776</td>
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<td>QMP32</td>
<td>-0.25</td>
<td>-0.35</td>
<td>-1.50</td>
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<tr>
<td>STF50</td>
<td>-0.70</td>
<td>0.30</td>
<td>-2.59</td>
<td>2.57</td>
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<tr>
<td>STF51</td>
<td>-1.10</td>
<td>0.90</td>
<td>-2.49</td>
<td>2.46</td>
<td>3146760</td>
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<td>STF70</td>
<td>-0.525</td>
<td>0.425</td>
<td>-2.48</td>
<td>2.49</td>
<td>4744150</td>
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<tr>
<td>STF71</td>
<td>-0.40</td>
<td>0.60</td>
<td>-2.46</td>
<td>2.49</td>
<td>4746650</td>
</tr>
<tr>
<td>QMP26</td>
<td>-0.25</td>
<td>0.45</td>
<td>-1.50</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>QMP29</td>
<td>-1.50</td>
<td>-0.20</td>
<td>-1.50</td>
<td>1.50</td>
<td>4749570</td>
</tr>
</tbody>
</table>

2010

2011

2012
For particles with the same impact angle, the torque applied to the crystals causes different relative angles with respect to the crystal planes. The difference if proportional to the $y$ impact location.

This effect is defined as torsion. As a result, the channeling efficiency varies with both the horizontal impact angle and the vertical impact position.

The channeling efficiency is defined as the number of channeled particles normalized to the total number of particles

$$\text{efficiency} = \frac{\text{Channeled Event}}{\text{Total Event}}$$

Channeled events are calculated from the deflection profile.
The center of gravity of each stripes on the impact y point axis gives the mean impact x angle as a function of vertical impact position.

2-dimensional efficiency plot as a function of impact x angle and impact y points is obtained.
Efficiency vs. Impact angle x vs. Impact y

The linear regression gives the torsion value and the initial impact angle offset.

\[ \chi^2 / \text{ndf} = 3.476 / 64 \]
\[ p_0 = -9.92 \pm 0.5784 \]
\[ p_1 = 7.358 \pm 0.5645 \]
If we define the impact x angle as

$$\theta_{corr}(x) = g.Pos(x) + \theta_{in}(x) - g.Pos_{init}(x)$$

The torsion correction made is

$$\theta_{corr}(x) - \left(torsion \ast Impact(y) + g.Pos_{offset}(x)\right)$$

The plots show the x deflection as a function of the impact x angle before and after the torsion correction.
The calculated torsions are summarized in this table:

<table>
<thead>
<tr>
<th>Xtal</th>
<th>Initial gonio angle [μrad]</th>
<th>Initial gonio angle [μrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STF38</td>
<td>-5.032</td>
<td>-5.515</td>
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<td>STF45</td>
<td>7.358</td>
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<td>STF47</td>
<td>-2.521</td>
<td>1.753</td>
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<td>STF48</td>
<td>6.942</td>
<td>7.285</td>
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<td>STF49</td>
<td>5.310</td>
<td>5.285</td>
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<td>-0.25</td>
<td>-0.35</td>
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<td>4.998</td>
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<tr>
<td>QMP29</td>
<td>-0.343</td>
<td>-0.873</td>
</tr>
</tbody>
</table>

2010

2011

2012
# Channeling efficiency recap

That is the recap of the channeling efficiency for the analyzed crystals.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crystal</th>
<th>±5 μrad</th>
<th>±10 μrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>STF45</td>
<td>0.69</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>QMP27</td>
<td>0.589</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Crystal</th>
<th>±5 μrad</th>
<th>±10 μrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>STF47</td>
<td>0.56</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>STF48</td>
<td>0.55</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>STF49</td>
<td>0.47</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>QMP32</td>
<td>0.51</td>
<td>0.41</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Crystal</th>
<th>±5 μrad</th>
<th>±10 μrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>STF50</td>
<td>0.56</td>
<td>0.46</td>
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<tr>
<td></td>
<td>STF51</td>
<td>0.52</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>QMP29</td>
<td>0.66</td>
<td>0.56</td>
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</table>
Dechanneling length recap

That is the recap of the dechanneling length

<table>
<thead>
<tr>
<th>Year</th>
<th>Xtal</th>
<th>± 5 μrad</th>
<th>± 10 μrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>STF45</td>
<td>1.43</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>QMP27</td>
<td>1.15</td>
<td>1.35</td>
</tr>
<tr>
<td>2011</td>
<td>STF48</td>
<td>1.525</td>
<td>1.414</td>
</tr>
<tr>
<td></td>
<td>STF49</td>
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<td></td>
<td>QMP32</td>
<td>0.42</td>
<td>0.37</td>
</tr>
<tr>
<td>2012</td>
<td>STF50</td>
<td>1.52</td>
<td>1.37</td>
</tr>
</tbody>
</table>
• 2010 data [/2010_09_16,_H8_re-recodata]
  – reconstruction problem
    » Each variable is in the array “thetaln_x”, inside the “tracks” branch
  – The data was reprocessed because of a bug, but some interesting run is still missing

• 2011 data [/2011_09_07_recodata4]
  – Optimization problem
    » Each variable in some branch is an array (100 place), of which only the first spot (0) is the real data (should be reprocessed from CMS)

• 2012 data [/2012_10_12_H8_protons/Data1]
  [/2012_10_12_H8_protons/Data2][/TB_22_06_2012_recodata]
  – Tree optimized and “performant”
    » But run collected in different folder
  – data in [/TB_22_06_2012_recodata] is in a tree 2011 like

• Issue: several run is missing, so some crystals are unanalyzable
### Xtla code

<table>
<thead>
<tr>
<th>Year</th>
<th>Nominal Property</th>
<th>Analyzed run</th>
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<tbody>
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<td>y(mm)</td>
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<td>STF40A</td>
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<td>STF45A</td>
<td>2010</td>
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<tr>
<td>STF71</td>
<td>2012</td>
<td>1</td>
</tr>
</tbody>
</table>

### Missing re-recoData

- **2010**

### Missing angular scan

### Missing Hi stat ch

### Bad Angular Scan

- Moving backward
Volume capture analysis

We define the region of captured particle as the area within $3 \sigma$ of the trend of the channeled spot.

The captured population is plotted as a function of the impact $x$ angle. The rise in the end of reflection region is a well-known behavior.

This analysis is performed for the first time, we are looking for a model that describes the trends observed.
Dechanneling Length
± 10 μrad

dTheta_x vs Impact_x tor Corr

<table>
<thead>
<tr>
<th>cut +/- 10 urad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
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<td>RMS</td>
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<td>$c^2 / \text{ndf}$</td>
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<td>Prob</td>
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<tr>
<td>p0</td>
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<td>p1</td>
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$d\theta_x$ vs $x$ tor Corr

$\Delta$ at ±10 μrad

$L_0 = 1.250 \text{ mm}$
Angle Scan Run Analysis

– Angular scan of the crystal, moving the goniometer on the horizontal plane respect to the beam
– We obtain both the scan of the angular kick with respect to the impact x angle and the goniometer position

• From the second one we get three stripes in which each effect is quite evident, and we analyze the peak of AM, CH and VR
  – NB : That’s only a check, before torsion correction, so we don’t know yet what is the impact angle respect the crystallographic plane. So for each stripes all the beam divergence is accepted.
x deflection vs. impact angle x

Down here is subtracted the initial angle scan of the goniometer
x deflection vs. the goniometer position on the horizontal plane.

Down here is subtracted the initial angle scan of the goniometer.
# Agnle Scan Analysis Recap

<table>
<thead>
<tr>
<th>Xtlc code</th>
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<th>Measurements</th>
<th>ch peak [μrad]</th>
<th>vr peak [μrad]</th>
<th>am peak [μrad]</th>
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*Note – VR sigma should be 1,387 μrad, which have to be added to the AM spread.*
Angular kick as function of $x$ and $y$ impact point is measured

- The $x$ cut is performed where a deflection appear in $x$ deflection and where a spread due to multiple scattering appear in the $y$ deflection plot.

- Most of the case the $y$ height of the crystal contains the $y$ dimension of the beam
  
  - $y$ cut : $\pm 3 \sigma$ from the mean of the $y$ beam profile
We measure the channeling efficiency (#ch/#tot) versus the impact point on the plane xy.

Note:

- We get a pixeled map of the xy plane. Each pixel have as dimension the spatial tracker resolution (50/60 μm).
- For each pixel we analyze the 1dim histogram of the angular kick inferred to each particle. A gaussian fit is performed around the CH peak.
- The channeling event are measured in two different way, depending on the crystal bending:
  - Bending > 90 μrad: event counted inside the 3σ from the mean of the fit.
  - Bending ~ 50 μrad: gaussian fit integral (because of the overlapped events in the tail).
QM cut

We get a map of the channeling efficiency in each pixel. Then we chose a zone where the efficiency is higher than 0.5 and with a minimal fluctuation.

QMP27

\[
x = [-0.4; 0.0] \\
y = [-1.5; 1.5]
\]
Torsion correction

STF47

\[ \theta_{\text{corr}}(x) = g \cdot \text{Pos}(x) + \theta_{\text{in}}(x) - g \cdot \text{Pos}_{\text{init}}(x) - (\text{torsion} \cdot \text{Impact}(y) + g \cdot \text{Pos}_{\text{offset}}(x)) \]

\(\text{dTheta}_x \text{ vs } \text{Impact}_x\)

\(\text{dTheta}_x \text{ vs } \text{Impact}_x\) nocut

22/08/14

R. Rossi - H8 crystal data analysis
Channeling Efficiency

± 2.5 μrad

Efficiency = 0.74

dTheta_x vs Impact_x tor Corr

Efficiency = 0.74
Channeling Efficiency

± 5 μrad

Efficiency = 0.69
Channeling Efficiency

± 10 μrad

Efficiency = 0.53
• x kick vs. impact y position is analyzed to measure the bending variation as a function of the vertical impact position

• The outgoing x angle vs. impact y position is also analyzed to measure directly the torsion as the variation of the outgoing angle as a function of vertical impact position

Geometrical cut is used for both the analysis
As we can see, a very slight variation of bending is present in this crystal.
This torsion value is comparable to the one obtained with the previous method.