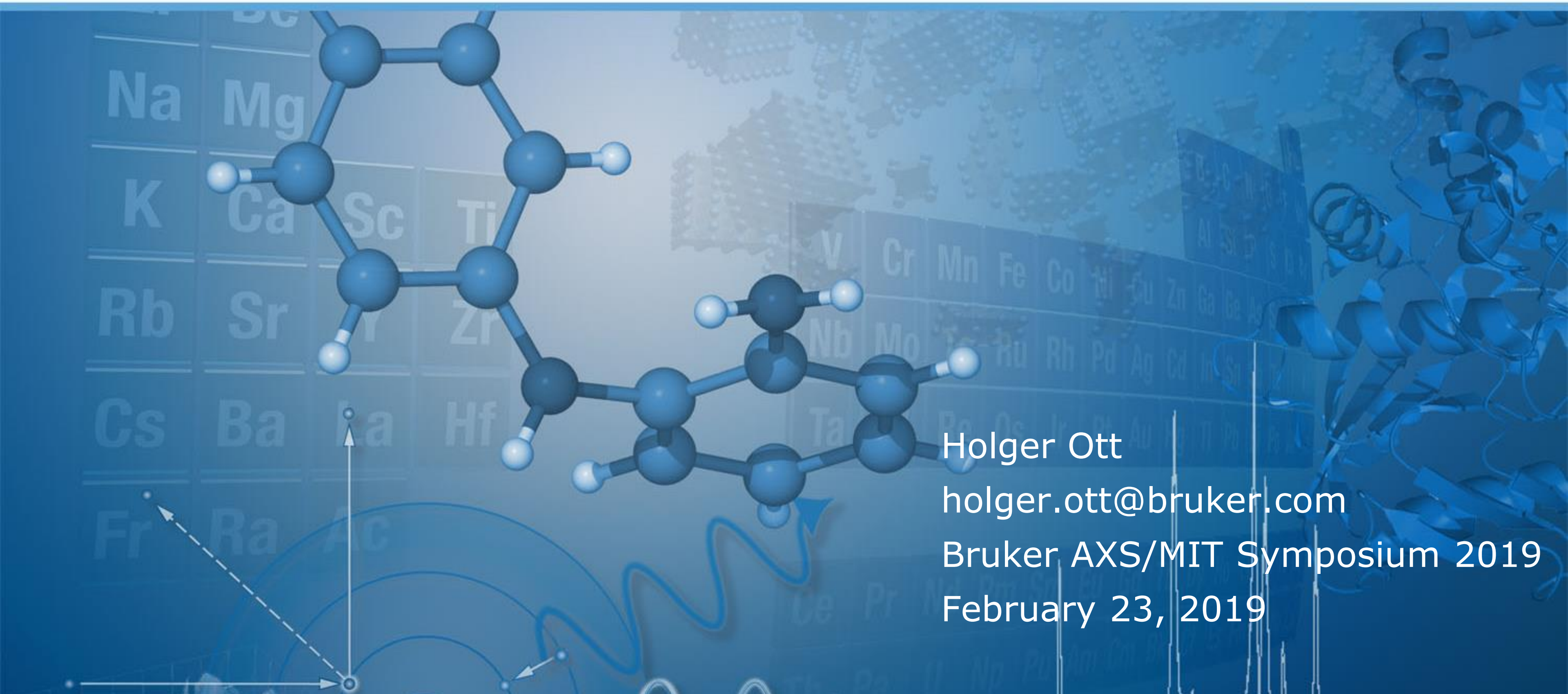
Accurate Experimental Charge Density Data: Tips & Tricks for Data Collection & Processing



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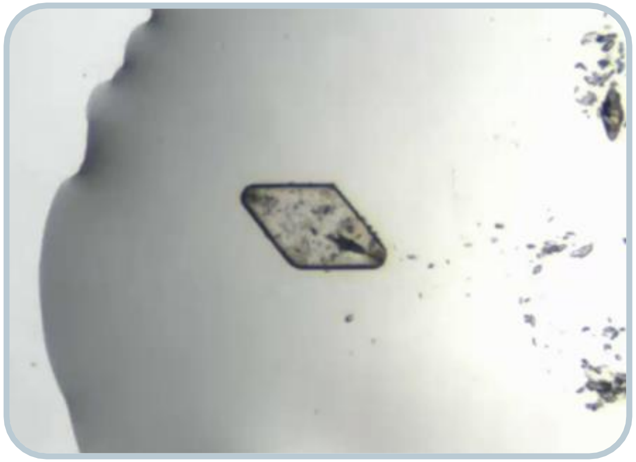
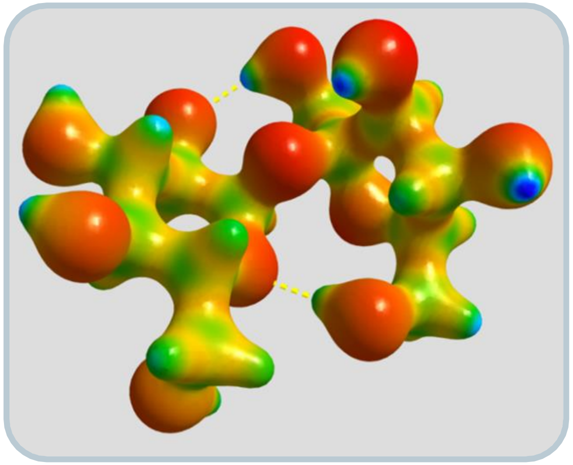
Bruker AXS/MIT Symposium 2019
February 23, 2019

Overview

- Before we start
- Experiment phase
- Data processing



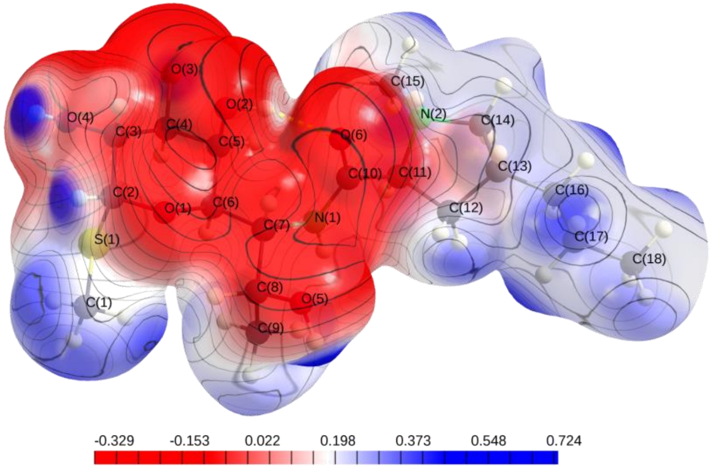


Charge Density Experiments: Survey

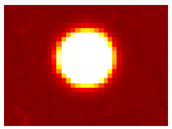
How many people in this rooms have done charge density data collections before?

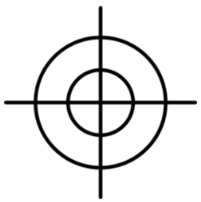
Who is doing them for less than 1 year?

Who is planning to do charge density experiments in the future?

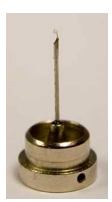


Charge Density Experiments: Anything to Consider Before We Start?





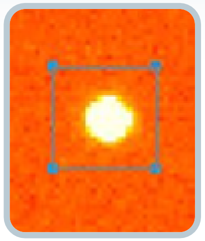


- Beam okay?
- Beam through goniometer center?
- Video microscope okay? Goniometer okay?
- Correct collimator on?
- Goniometer head properly fixed? Worn out?
- Magnet tight? (for pin mounting)
- Low-T okay? (no ice, no shadow, centered)
- How to mount the sample?

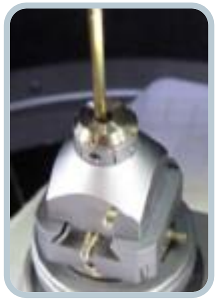
Checking the Instrument

We should make sure that the diffractometer is in good conditions before we start!



What to check:

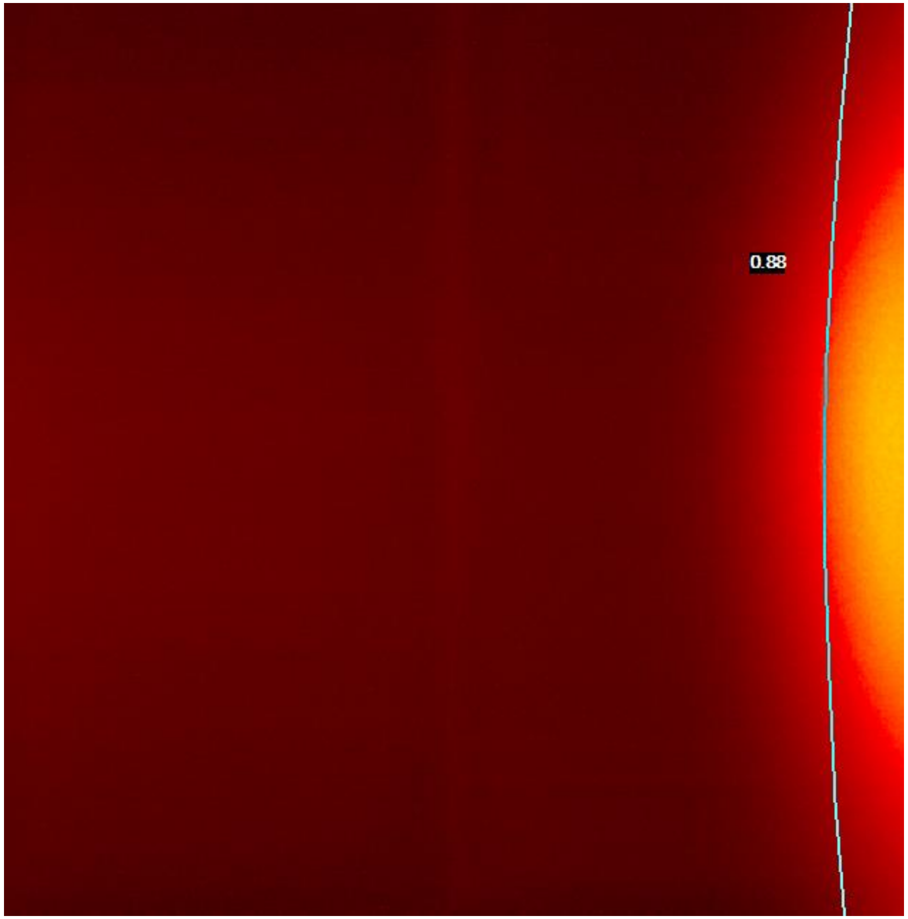
- Primary beam intensity still okay?
  - Comparing test shots from installation under \frames\alignment
  - Run ylid test crystal with same strategy as in "cust" project
- Beam passing through goniometer center?
  - Half beam alignment procedure (don't use steel ball shadow)
- Collimator fine?
  - Not clipping the beam (IµS ~3 % counts; removed air scatter)
  - No diffuse background around beam stop
- Beam stop good?
  - Right size (low res. reflections important; now long axis beam stop available)
  - Properly centered (important for beam stop masking)
  - No back scattering at high resolution!



Checking the Instrument

When the beam stop “shoots back”!

Low-res.



High-res.

Checking the Instrument

- Corrections: 2θ zero adjusted?
- Beam center, detector distance, detector rotations set?
- Vertical beam tilt & omega zero okay?
    - Check the „unconstraint global unit cell“ angles of the ylid crystal.
    - They should be well within ± 0.03 deg. Otherwise, modify the tilt angle in Determine Unit Cell - Unit Cells - Edit and recheck. Apply corrections again if needed

Please note: Don’t modify the Chi angle on the goniometers!

Least-Squares Parameters	
roll [°]	-0.00
yaw [°]	-0.19
☑ **Goniometer zeros**	
ω [°]	-0.14
χ or κ [°]	0.12
☐ X-ray source	
wavelength [Å]	0.56087
tilt [°]	0.05

- Low temperature nozzle perfectly centered above crystal?
- Goniometer head tight (check carefully during crystal centering)

- Magnet fixed?
- Attenuator stored (used during beam check)/ unchecked BIS option?

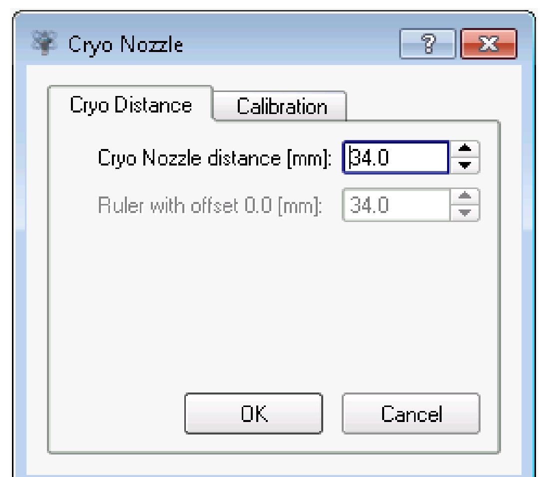
Low-Temperature Device

Needs to be:

- Stable
- Operating ice-free for a long time (1 - 14 days):
  - Slim brass/copper pin (I prefer ALS style pins)
  - Adjust shield stream to achieve a laminar flow
  - Comply with service intervals of shield stream compressor
  - Magic angle of a FIXED-CHI beneficial for minimal turbulences; Chi angle can be limited on a KAPPA with coolerlowkappa and coolerhighkappa commands in the bn-config.py file
  - Sometimes better to switch cabinet fans off (DIFFRAC.TOOLS - Enclosure)
- Reach the lowest possible temperature (deconvolute ED from atomic movement; avoid thermal diffuse scattering, TDS)

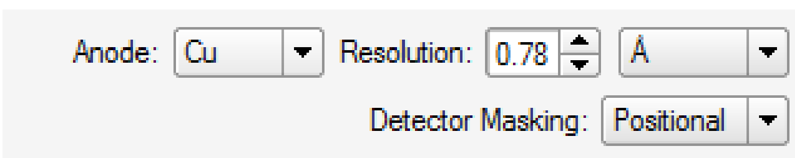
Low-Temperature Device

- Should not shade detector area, but sometimes this is not possible
- In the past one had to rely on the active mask creation (do not use with PHOTON detectors), paint a custom mask file or use the outlier masking in SADABS
- Now, you can add the Cryostream 700/800, Helix, or Kryoflex II to the Goniometer Viewer
- The current cryo nozzle distance can be updated under Instrument - Update Cryo Nozzle Distance…

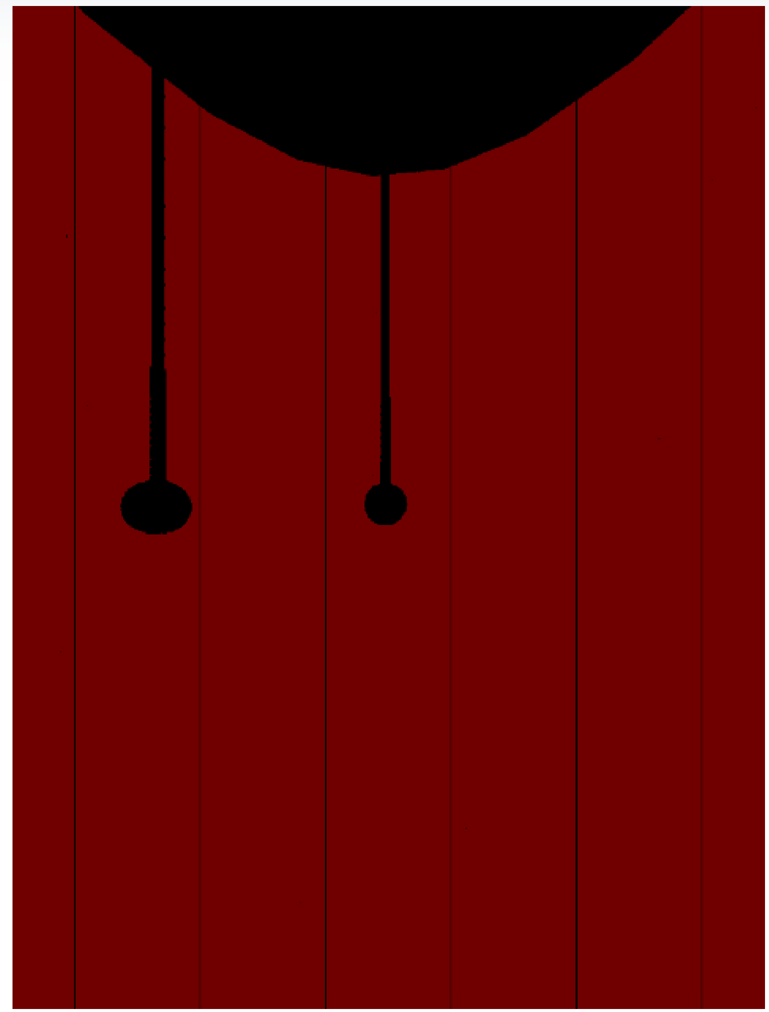


Mask File

- The name_xa_0X_0001.sfrm file contains the cryo nozzle shadow as an integration mask
- The 2019.1 version can make use of the mask file to improve the strategy optimization.



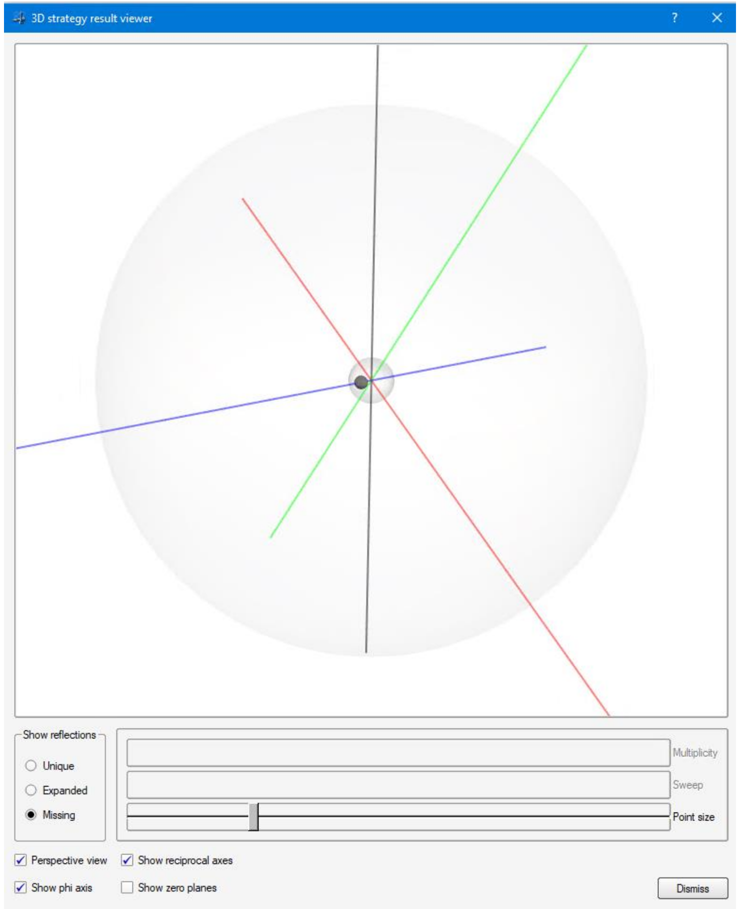
- The options are (cummulative):
  "**Not used**": only beam catcher is considered
  "**Basic**": bad pixels are considered
  "**Positional**": beam stop holder and cryo nozzle shadow



Mask File

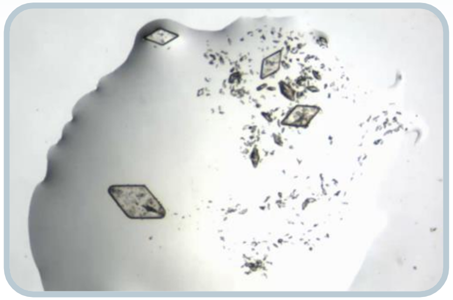
```
P90 multiplicity:       3.8          Missing reflections:      1      (Beamstop reflections: 1)
Average multiplicity:   5.0          Completeness:         99.92 %
```

- Inspection of missing reflections with the 3D strategy result viewer
- Additional sphere shows beamstop shaded area
- Number of affected reflections are listed now



Ready to Go?!

The CRYSTAL

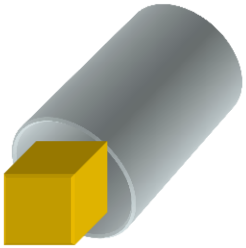


- Find the perfect imperfect crystal!

  i.e. no splitting, twinning, (localized diffuse scattering)
  sufficient mosaicity to minimize extinction effects

- Try to match the crystal size with the beam.
  Scaling can compensate for crystal volume effects

- Shape ideally isotropic



The Driver

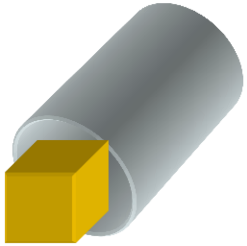
- Take your time for the preparation and the design of the experiment

- Make sure that you got enough beam time

Ready to Go?!

Crystal Size

- Regular fine-focus sealed tube beams can be tuned in size with the collimators. Don’t use a too large collimator for a smaller crystal, as you increase the diffuse background and affect the $I/\sigma(I)$.
- Modern microfocus (rotating anode or sealed-tube) sources provide fine Gaussian-type beam profiles around 100 micron in FWHM.
  - Ideally, the crystal should fully “bath” in beam. However, this is not always possible for charge density research, because the diffraction power of a 100 micron crystal may not be sufficient to achieve the required resolution.
  - Depending on the content of the crystal a larger crystal size may also work. The weaker absorbing the sample, the larger the size can be. 300 to 400 microns normally work for organic samples, heavier absorbing samples should be smaller



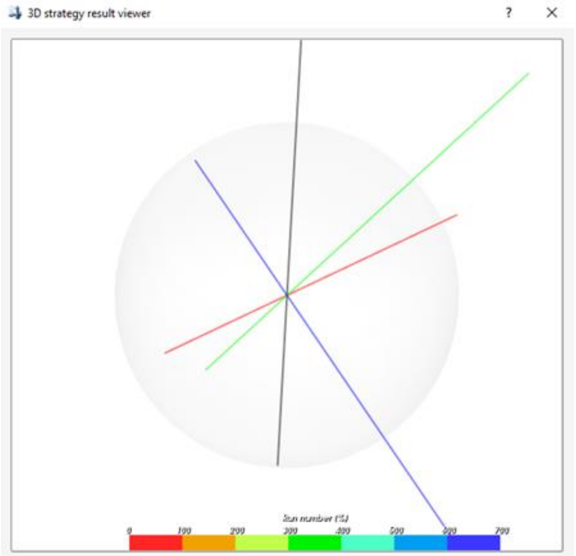
Sample Mount

Requirements:

- Stable crystal position (i.e. no nylon loops, thin glass fibers)
- Minimal interference with cold stream
- As little oil or other crystal fixation means as possible

  ⇨ The diffuse background signal is limiting the crude I/σ(I) for photon counting detectors

- Crystal should preferable not be aligned along the phi axis



Starting the Experiment

GCP (Good Crystallography Practice): Crystal Centering

1. Mount sample and center the crystal properly
2. Start Fast Scan (even 370 deg phi scan, ≤ 0.5 deg steps)
3. Determine unit cell
4. Calculate strategy
5. **Re-center** crystal now that the sample holder/gonio-head is cold (in tricky cases consult crystal translations in Determine Unit Cell or use X-ray centering with the AGH)
6. Start data collection

Starting the Experiment

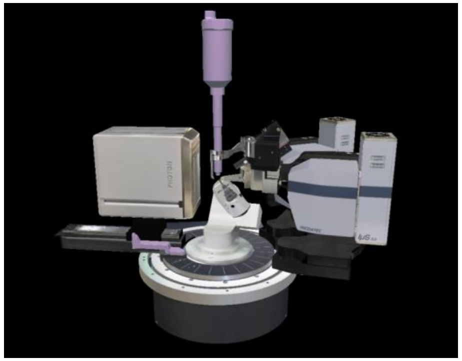
GCP: Basics

Never leave the instrument before you see the first image!

Be aware of:

- Dummy beamstops
- Bent beamstop (mechanical stress or pushed by low-T nozzle)
- Removed beamstop on single source instruments
    - Cryo mounting
    - Desperate approach to get low resolution reflections

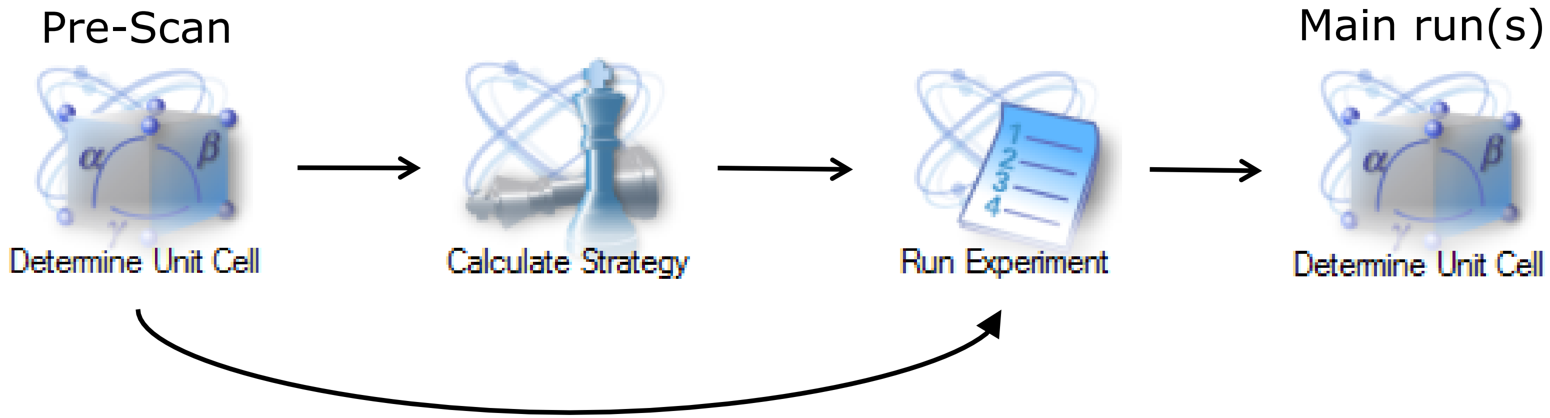
Always check the goniometer viewer when you take over the diffractometer!



The Unit Cell Determination

GCP: Unit Cell determination

1. Determine Unit Cell from pre-scans
2. Start data collection (optimized or canned)
3. **Re-determine** unit cell from main runs

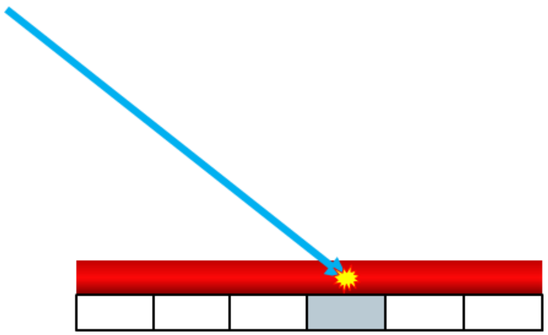


The Experiment Parameters

- **Detector distance** - Short is not always the best

  Consider:

  - Reflection overlap
  - Goniometer limits
  - Diffuse scattering signals drop off with $1/r^2$
  - Oblique/incident angle correction



Standard APEX II/PHOTON 100/PHOTON II/PHOTON III C have ~92 % phosphor efficiency for Mo and ~68 % for Ag radiation.

The more acute the reflections hit the detector, the more needs the intensity of the reflections at the edge of the detector be corrected (reduced)

The Experiment Parameters

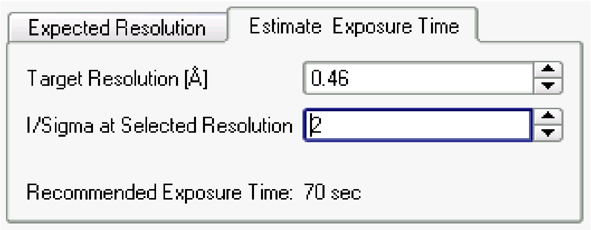
- **Resolution**
  - IUCr/Acta requirements: 0.464 Å (100 deg in 2θ for Mo)
  - There should be at least a data/parameter ratio after the multipole refinement of 10

- **Exposure time**
  - The software can help with the “Expected resolution” table or the new “Estimate Exposure Time” feature.
  - Make use of the available time!
    Increase exposure time or redundancy?

Expected resolution:

	Exposure time [s/°]	Resolution [Å]
1	2.0	0.95
2	5.0	0.89
3	10.0	0.86
4	20.0	0.82
5	30.0	0.80
6	45.0	0.79
7	60.0	0.77
8	90.0	0.76
9	120.0	0.75

- **Redundancy**
  - At least 30 for low resolution data in correct point group
  - More than 10 for the highest resolution shell

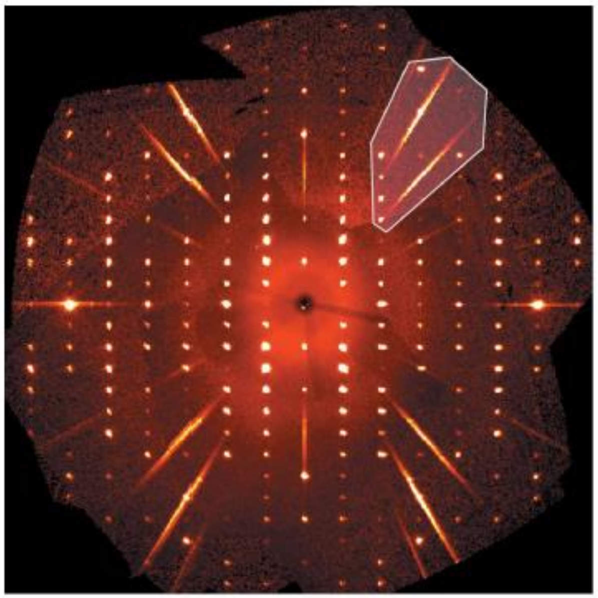


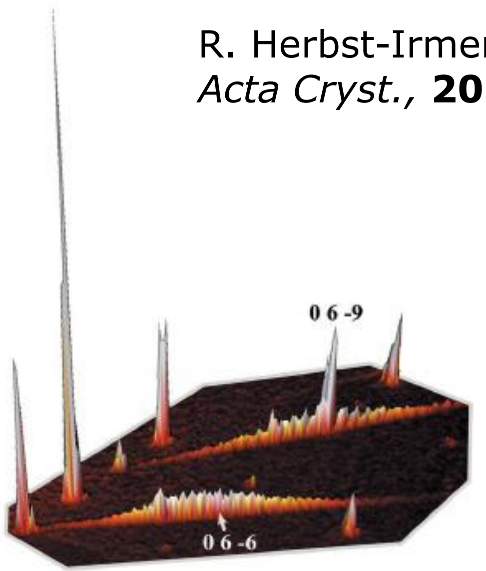
The Experiment Parameters

- **Chi limitation for KAPPA goniometers?**
  - Coolerlowkappa = 40.0
    Coolerhighkappa = 100.0
  - This reduced "ice-beard" formation and turbulences
  - Never go too low with chi, otherwise your crystal height will change!
    e.g. 50 microns at Chi = 10 deg
- Take off Cu beamstop on VENTURE dual wavelength systems

The Experiment Parameters

- **3λ Filter?!**
  - First described: Storm, A. B., Michaelsen, C., Oehr, A. & Hoffmann, C. (2004). Proc. SPIE, 5537, 177–181.
  - I recommend to use it for all mirror sources
  - 100 mu Al foil works



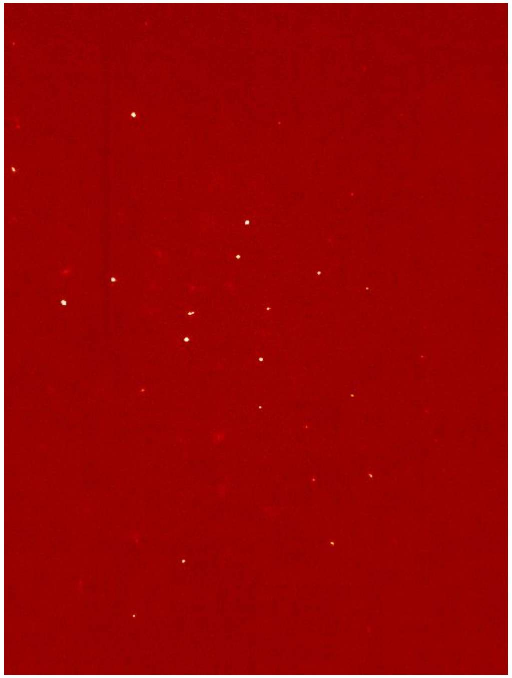


R. Herbst-Irmer, D. Stalke, *Acta Cryst.*, **2017**. B73, 531–543

Charge Density Strategy Optimization

2θ Detector Settings

- Large 10 (20) x 14 cm active detector area allows to collect high resolution data in one or just a few 2θ positions
- Regular strategy settings will lead only to high resolution runs (may minimize the need for data scaling)



Field of view @ 6 cm [deg]	PHOTON II/III 14	APEX II
Equatorially	80	54
Vertically	98	54
Diagonally	110	71

Charge Density Strategy Optimization

I recommend the following procedure:

1. Use fine slicing for charge density (0.25 to 0.5 deg steps; ultra fine slicing not required)
2. Optimize a low resolution data set using the correct point group with 2θ close to 0 deg (depending on wavelength and detector distance 0.65 to 0.80 Å) and add runs to experiment list.
3. Run strategy optimizer with correct point group from scratch (restart) asking for the desired resolution and append runs
4. Add a few medium resolution runs to the experiment
5. Import all runs to the optimizer, check redundancy, and extend strategy for a lower symmetry
6. Add 1 to 3 fast scans with different exposure times, but similar scan width
7. New for PHOTON III detectors: Mix sensitive and dynamic mode runs (for weakly diffracting samples more sensitive mode runs at high 2θ)

Charge Density Strategy Optimization

Dynamic Range Considerations

- Pixels may get saturated when too many X-rays are collected
- Reflections that contain saturated pixels are automatically rejected during the integration step and may affect data completeness
- Data collection strategy should include a set of **"Fast Scans"**
- These are quick low 2θ runs in which no pixel gets saturated. This is achieved by reducing the exposure time, (increasing the scan width), or attenuating the primary beam
- Fast scans are treated separately during scaling

	Operation	Active	Distance [mm]	2Theta [deg]	Omega [deg]	Phi [deg]	Chi [deg]	Time [sec]	Width [deg]
1	Fast Scan	Yes	50.000	0.000	0.000	0.000	54.740	1.000	1.000

Scan	Fast Scan	Domain	2-Theta	R(int)	Incid. Factors	Diffr. Factors	K	g	I/s(lim)	Total	I>2sig(I)
✓ 1f	✓										
		1	0.0	0.2726	0.864 - 0.981	0.965 - 1.050	1.153	0.0167	59.8	6863	2581
✓ 2	☐										
		1	3.1	0.0495	0.878 - 1.026	0.965 - 1.026	1.042	0.0167	59.8	3874	2624

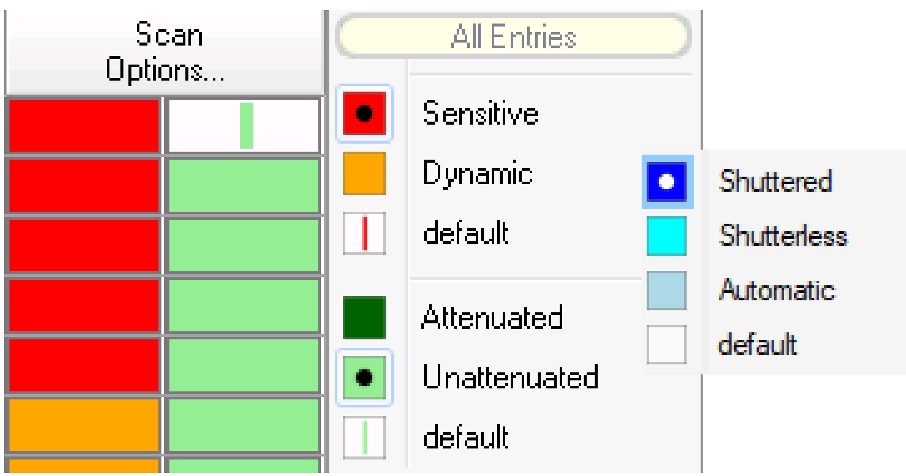
- CCD charge density results are also positively affected by using quick scans rather than an overflow protection ("retake if topped" option)

Charge Density Strategy Optimization

New features in the Run Experiment plugin

Different detector modes and attenuation settings are now available in the experiment table:

- PHOTON III: Dynamic (PHOTON II charge integration mode) or Sensitive mode (MIXED MODE, photon counting & charge integration)
- PHOTON 100: Shuttered or Shutterless operation
- CCDs: Automatic, uncorrelated or correlated images
- Attenuation: rotary absorber foil in/out



Charge Density Strategy Optimization

- **Exposure Times**
  - The longer the exposure time, the less detector noise in the charge integration mode/dynamic mode (until the detector is noise free)
  - Long exposure times lead to more Zinger contamination on uncorrelated images without the PHOTON III HEED feature (high energy event discrimination)

  - **My procedure:**
    1. I assign a "guessed" (you can also rely on the software suggestions) exposure to the different 2θ settings and inspect the diffraction pattern after a few images. If necessary, I try longer/shorter exposure times.
    2. Modify the experiment list accordingly by hand or since 2017.3, you can also use the theta dependent exposure time function of the strategy optimizer.
    3. Finally slightly alter the exposure time of the later runs by hand, so that you avoid using just a single exposure time per detector setting

Charge Density Strategy Optimization

Example: Ag Strategy

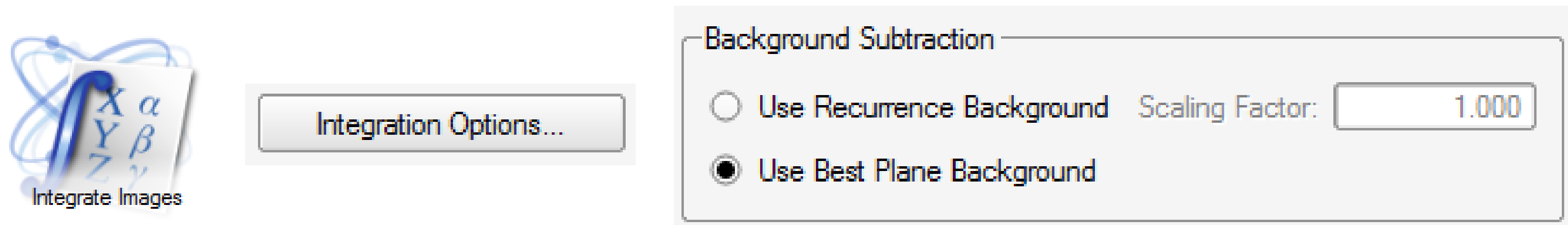
	Operation	Active...	Distance [mm]	2Theta [deg]	Omega [deg]	Phi [deg]	Chi [deg]	Scan Options...	Time [sec]	Width [deg]	Sweep [deg]	Direction
1	Phi Scan	Yes	50.044	0.000	-12.000	0.000	54.736		1.000	0.500	360.000	positive
2	Omega Scan	Yes	50.044	9.713	-182.038	282.000	54.736		5.000	0.500	203.500	positive
3	Phi Scan	Yes	50.044	9.713	21.463	114.000	54.736		5.000	0.500	212.000	positive
4	Omega Scan	Yes	50.044	34.924	-156.827	-40.000	54.736		60.000	0.500	203.500	positive
5	Omega Scan	Yes	50.044	34.924	-156.827	-120.000	54.736		60.000	0.500	203.500	positive
6	Omega Scan	Yes	50.044	34.924	-156.827	80.000	54.736		60.000	0.500	203.500	positive
7	Omega Scan	Yes	50.044	34.924	-156.827	160.000	54.736		60.000	0.500	203.500	positive
8	Omega Scan	Yes	50.044	0.000	12.000	0.000	54.736		2.000	0.500	203.500	automatic
9	Omega Scan	Yes	50.044	0.000	12.000	240.000	54.736		3.000	0.500	203.500	automatic
10	Omega Scan	Yes	50.044	40.102	-151.649	-80.000	54.736		75.000	0.500	203.500	positive
11	Omega Scan	Yes	50.044	40.102	-151.649	-40.000	54.736		90.000	0.500	203.500	positive
12	Omega Scan	Yes	50.044	19.997	-171.754	-54.000	54.736		20.000	0.500	203.500	positive
13	Omega Scan	Yes	50.044	19.997	-171.754	153.000	54.736		30.000	0.500	203.500	positive
14	Phi Scan	Yes	50.044	19.997	-171.752	-86.892	54.736		45.000	0.500	230.000	positive
15	Omega Scan	Yes	50.044	9.713	-182.038	10.000	54.736		10.000	0.500	203.500	positive
16	Omega Scan	Yes	50.044	9.713	21.463	204.000	54.736		15.000	0.500	203.500	automatic
17	Omega Scan	Yes	50.044	9.713	21.463	100.000	54.736		20.000	0.500	203.500	automatic
18	Omega Scan	Yes	50.044	40.102	-151.649	180.000	54.736		90.000	0.500	203.500	positive
19	Phi Scan	Yes	50.044	-10.000	-180.000	0.000	54.736		7.000	0.500	370.000	positive

⇦ Fast Scan (row 1)
⇦ Low res. (rows 2–3)
⇦ High res. (rows 4–7)
⇦ Low res. (rows 8–9)
⇦ High res. redundancy (rows 10–11)
⇦ Med res. (rows 12–14)
⇦ Low res. redundancy (rows 15–17)

Data Work-Up

Integration

- Try different background determination methods:
  I strongly recommend to use the "Best Plane" method (especially useful for diffuse signals)



Does that change anything?
Charge Density: highest res. density dropped from 0.9 to 0.5 e/Å^3
High Pressure Data: *R*1 dropped from 12 to 2 %

Do you like to make that mode the default?

Create a text file on C:\ called saint.ini with the following entries:
[INTEGRATE]
PLANEBG=1

Data Work-Up

Integration

- Check different profile fitting thresholds (default 8 I/σ(I)).
- Keep an eye on the frame queue half width. The default (7) may be too small for fine sliced data.
- High resolution cut-off for low resolution runs, if data gets weak at the corners of the detector.
  "Negative" side-effect of large detectors: they may be hard to fully "illuminate".

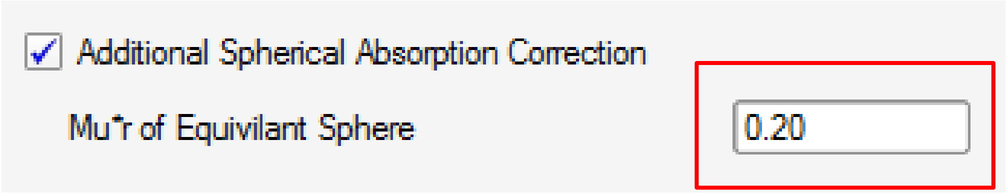
  One can set individual high resolution cut-offs for each run with the new SAINT version. For the moment being, this can be only done with the command line version by modifying the saint.ini, but we are working on a GUI implementation

Data Work-Up

Absorption and Scaling: Scale plug-in (GUI for SADABS)

Generally, the most likely data processing step where people ruin their data!

- Scaling is essential for micro-focus sources!
- It **ONLY** works with the correct Laue (or point) group
- Some less known tweaks:
  - Additional spherical absorption correction factor

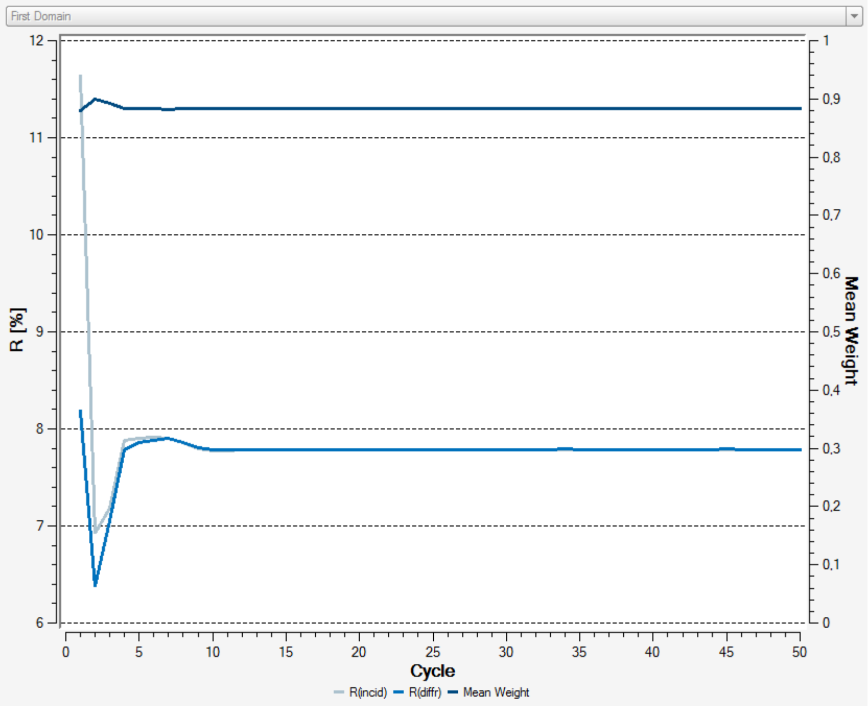


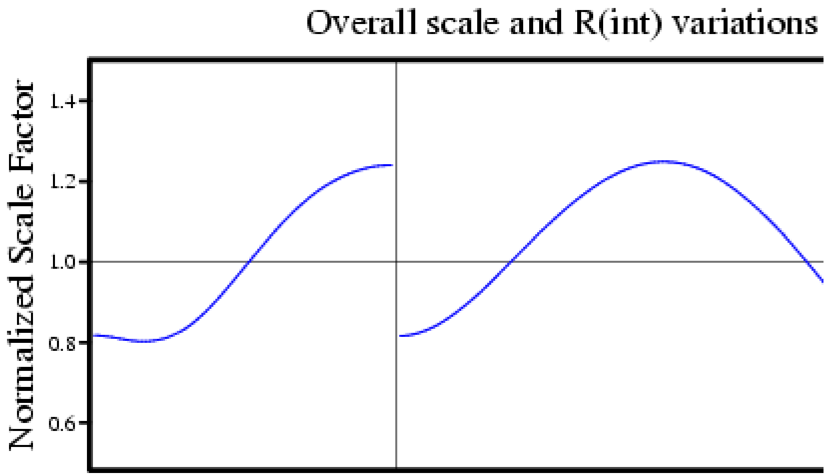
  - The empirical (multi-scan) absorption correction method is 2θ independent.
  - In order to include the dependency, calculate the product of the **absorption coefficient** and **crystal radius**
  - Does it matter? If the product > 0.5, your residual density will become more asymmetric, the ADPs will shrink and the R1 is worse!

Data Work-Up

Absorption and Scaling

- Restraint ESD for Scale Factors
  - Symptoms to look for:

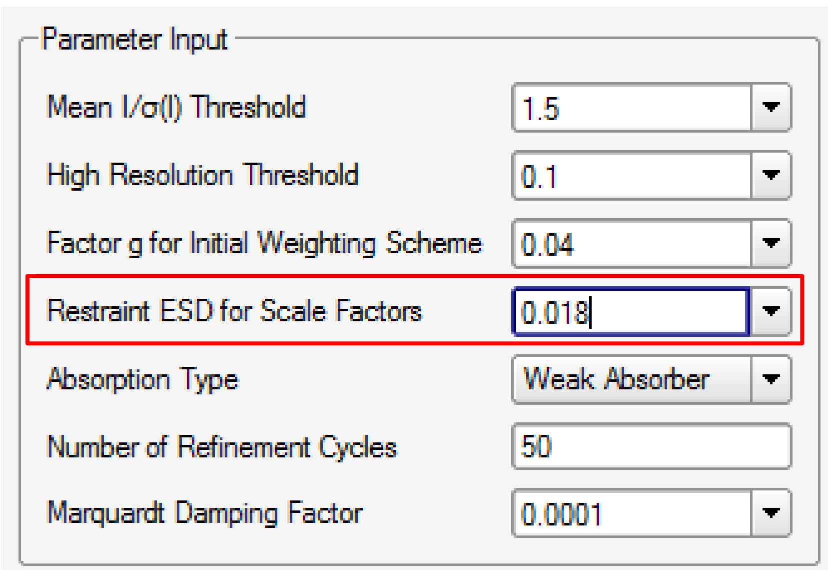


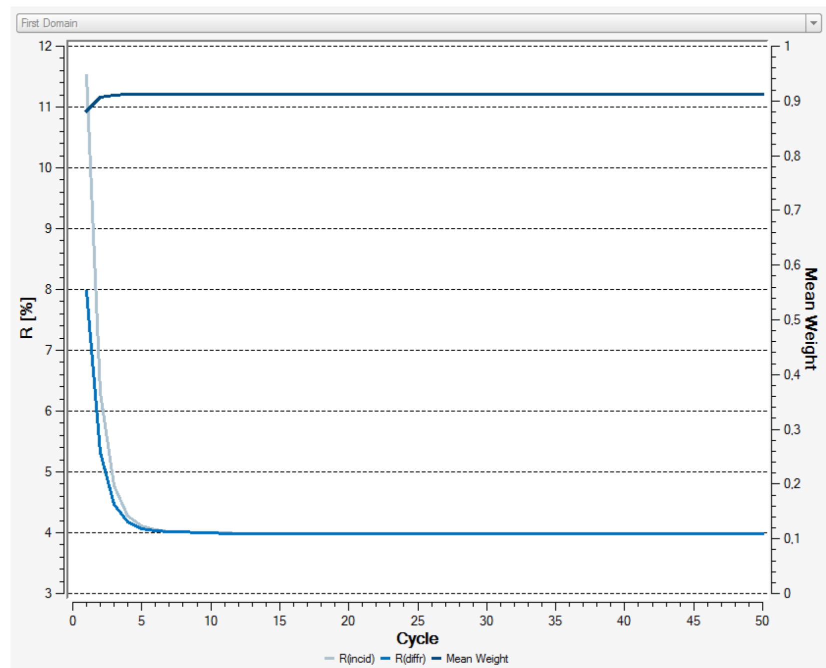


Data Work-Up

Absorption and Scaling

- Restraint ESD for Scale Factors
  - The cure: Increase the value (default 0.005)

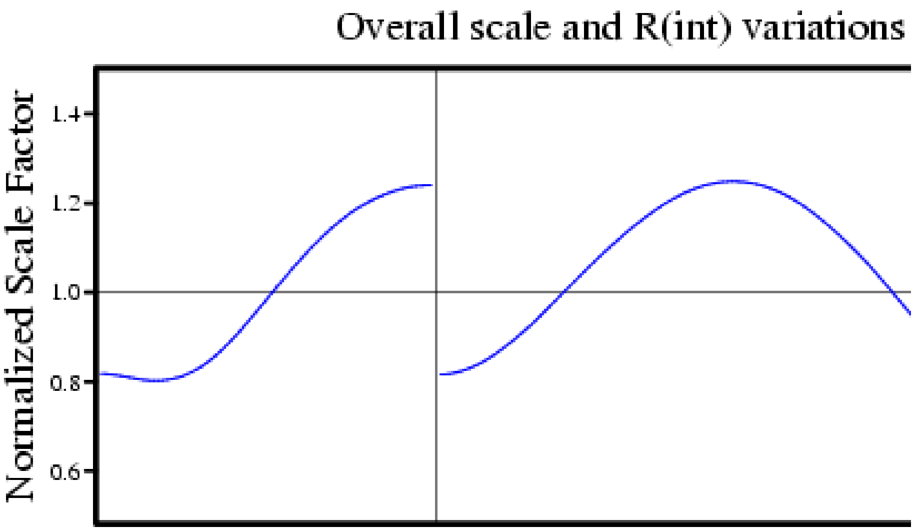




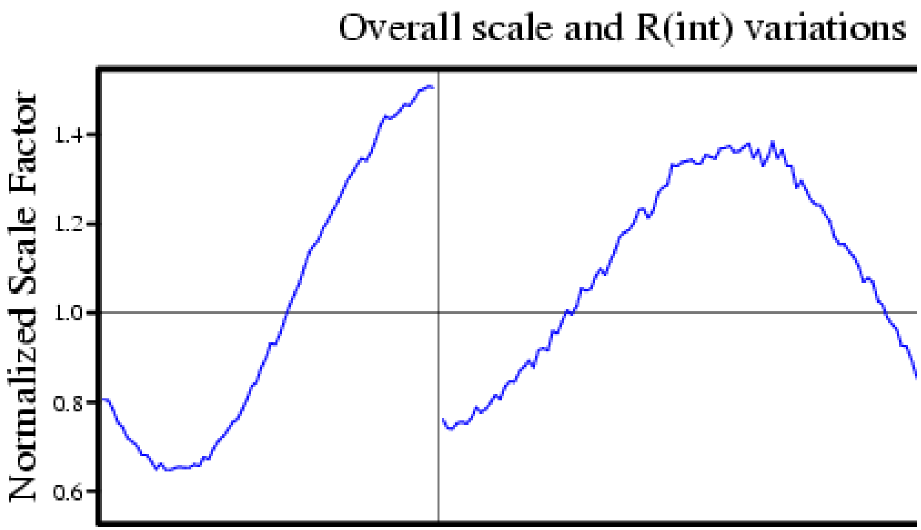
Data Work-Up

Absorption and Scaling

- Restraint ESD for Scale Factors
  - The cure: Increase the value (default 0.005)



Before



After

  - Or do a numerical absorption correction (crystal must not exceed the beam)

Data Work-Up

Absorption and Scaling

- Make use of the diagnostic plots/numbers to identify outliers
- Use charge density settings for the error model part: g = 0; K = 1
  Available on the command line (non-expert mode):

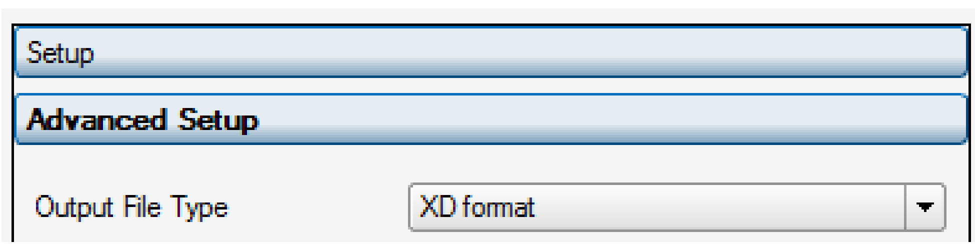
```
PART 2 - Reject outliers and establish error model

Rejected reflections are ignored in the statistics and Postscript plots
(except the detector diagnostics) and in the output .hkl file
Before applying rejections there are:

  34754 total and    450 unique reflections assuming Friedel's law
plus    690 total and    15 unique reflections in fast scans

Reflections rejected for which |I-<I>|/su >   4.00
where:  su^2 = sigma(I)^2 + (  0.04000 <I>)^2  (sigma(I) from SAINT)

  34733 total and    450 unique reflections left after |I-<I>|/su test
plus    687 total and    15 unique reflections in fast scans

su^2 = [K*sigma(I)]^2 + [g<I>]^2  where sigma(I) is from SAINT

K=1, g=0 (0), K=1, refine overall g (1), K=1, refine all g (2),
refine overall K and overall g (3), refine overall K and all g (4),
refine all K and overall g (5), refine all K and all g (6),
refine overall K, input fixed g (7), refine all K, input fixed g (8),
input fixed K, refine overall g (9), input fixed K, refine all g (10),
input fixed K and g (11) [5]: 0
```

Data Work-Up

Absorption and Scaling

- Write XD hkl (command line or Scale plug-in)

```
Repeat (R), write unmerged .hkl (W), merged .hkl (M), .sca (S), XD format (D),
modulated .hk6 (J), testxtl.dat (BioXhit) (T), unmerged with scan and frame
numbers (U) or quit (Q) [W]: d
Reflection output file [xd.hkl]:
Average Friedel opposites in output file (Y or N) [Y]:
Name of crystal for XD file header (one word): bruker
Omit zero or negative intensities (recommended for XD) [Y]:
Space group to eliminate systematic absences (e.g. P2(1)/c, R-3, Ccca): Fm-3m
```



Irons out systematic absences, averages data, and removes 0 or negative intensities and standard uncertainties

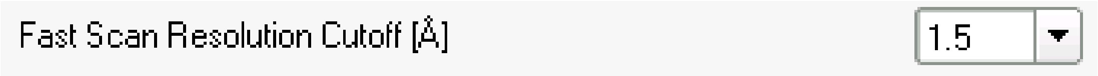
Data Work-Up

Absorption and Scaling

- λ/2 or 3λ corrections (command line or Scale plug-in)

```
Apply lambda/2 correction for a graphite monochromator (2) or lambda/3 for
Ge or Si monochromator (3) or 3-lambda for multilayer optics and Mo, Ag or In
radiation (4) or no correction (0) [0]: 4
Correction factor [0]: 0.0015
```

- Fast scan treatment
  - Take fast scans as regular runs if data quality is sufficient
  - Use the fast scan high resolution cut-off in the Advanced Options for weaker cases (or the option on the command line)




```
Specify scan numbers of 'fast' scans on one line separated by spaces (<Enter>
if none). These are only used to replace reflections suppressed by SAINT in
all other scans: 1 2

Resolution in Angstroms at which to truncate fast scans [1.5]:
```

Data Work-Up & (Weighting Scheme)

Standard Structure Quality Indicators

- XPREP statistics
- Consult regular quality criteria (APEX3, Olex2, WinGX)
- Inspect residual density like we learned yesterday
- Consider deeper validation methods (J. Henn, A. Thorn, …)

Data Work-Up & (Weighting Scheme)

Standard Structure Quality Indicators

- XPREP statistics
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XD refinement :

- Use $1/\sigma^2$ weights
- However, this often leads to large GoF values
- A way around: *CAPOW*: a standalone program for the calculation of optimal weighting parameters for least-squares crystallographic refinements (open access)

N. T. Johnson, H. Ott, M. Probert, *J. Appl. Cryst.*, **2018,** *51*, 200

Conclusion

- Accurate high quality data is the key for Quantum Crystallography
- You will only get that if you know your sample and instrument/software well and take your time

- Diffractometer and experimental conditions need to be very good
- A smart experiment design will pay off
- Data processing has a strong influence on the final data quality

- Don't get frustrated. The success rate will be far below 50 %

Innovation with Integrity