Towards multi-order hard x-ray imaging with multilayer zone plates

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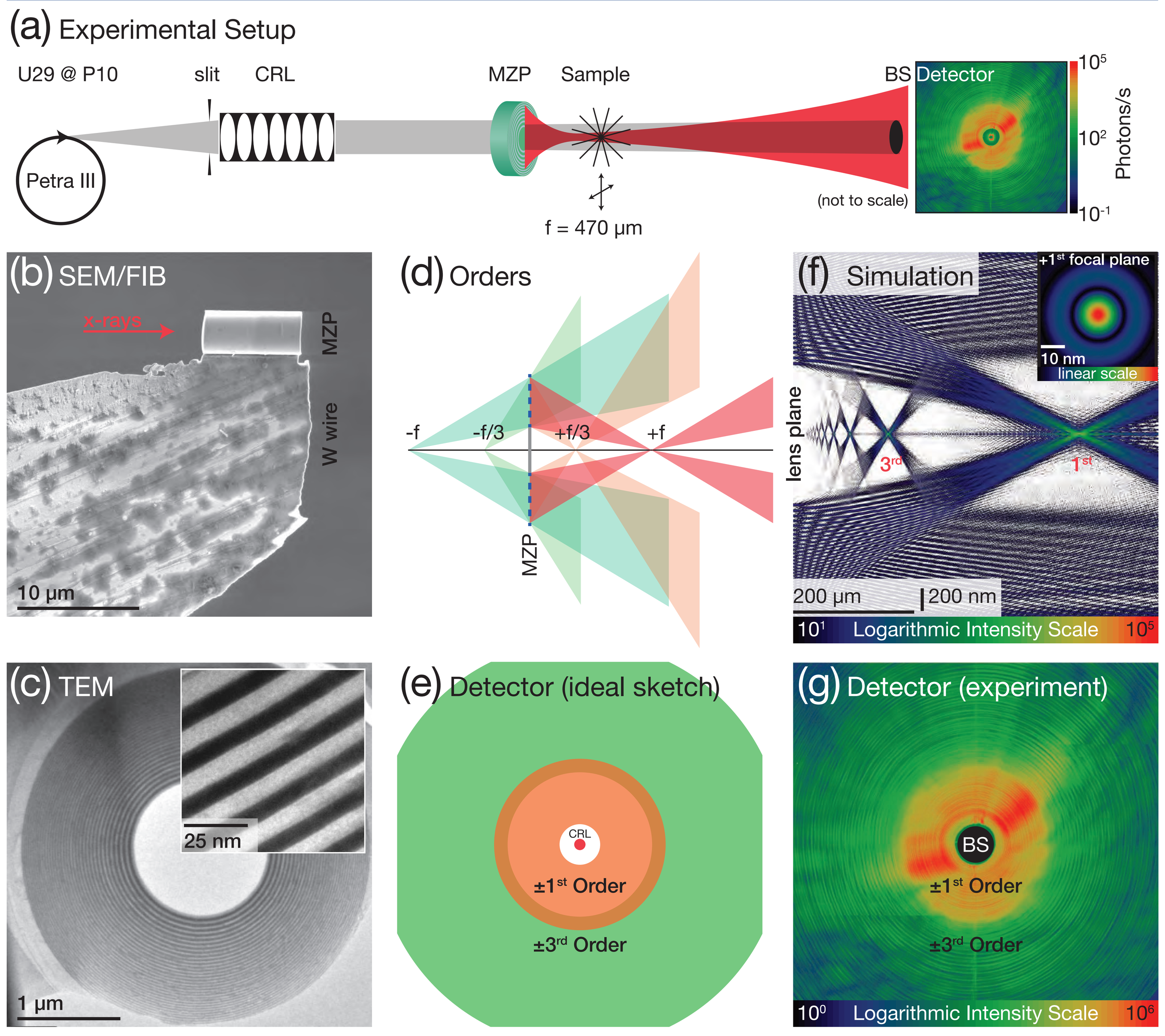
Multi-Order Zone Plates

a high-resolution Multilayer Zone Plate (MZP) focusing down to 5 ... 10 nm (2D, 7.9 < E < 18 keV); note that pre-focusing adapts the coherence length of > 50 µm to the lens size of < 5 µm
b lens fabrication with Focused Ion Beam
c overview and detail of MZP zone quality with TEM
d diffractive optics yield a multitude of focii:
can we image without an Order Sorting Aperture?
e idealised detector image to show than one can disentangle 1st from 3rd order (but +/- still remains)
f simulation of intensity along optical axis, showing +1st and +3rd order focus and higher orders; compare to d
g typical detector image; compare to e



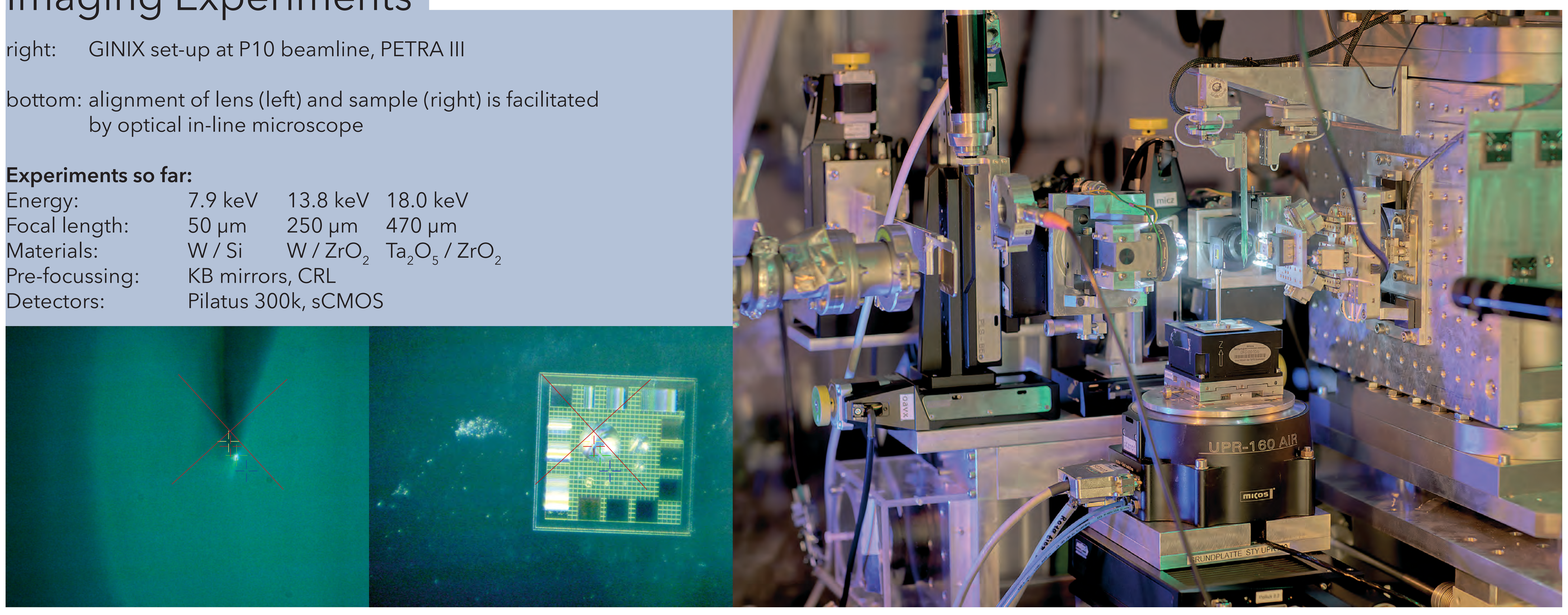
Imaging Experiments

right: GINIX set-up at P10 beamline, PETRA III

bottom: alignment of lens (left) and sample (right) is facilitated by optical in-line microscope

Experiments so far:

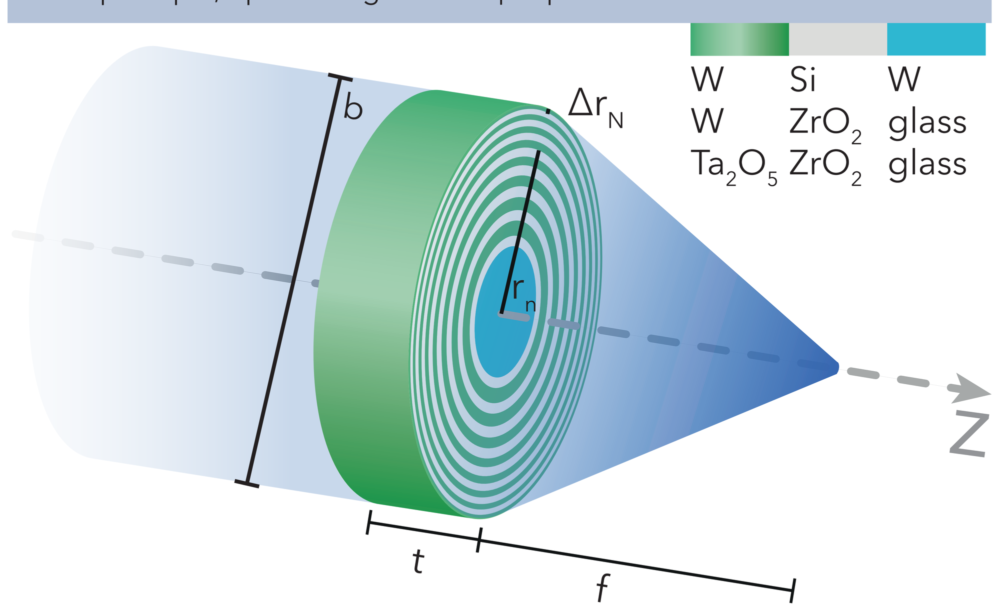
Energy:	7.9 keV	13.8 keV	18.0 keV
Focal length:	50 µm	250 µm	470 µm
Materials:	W / Si	W / ZrO_2	Ta_2O_5 / ZrO_2
Pre-focussing:	KB mirrors, CRL		
Detectors:	Pilatus 300k, sCMOS		



Göttingen MZP

Central core: thin glass fibre of 800 nm ≤ ø ≤ 2 µm; so far lenses with outer radius of r_N ≤ 7 µm fabricated by Pulsed Laser Deposition of alternating layers, optical thin and optical thick material, e.g. W / Si

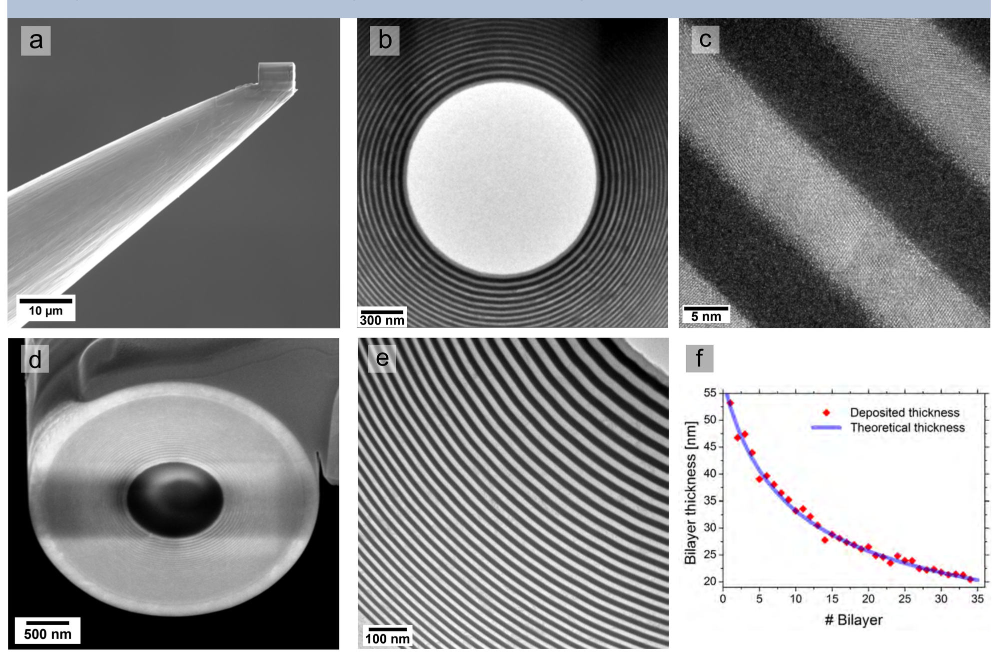
Best results found for material combination Ta_2O_5 and ZrO_2 found:
- very constant and high PLD rates during deposition,
- no droplet formation, opposed to Si,
- very clean and thin layers possible, up to 3 nm and below,
- *cumulative smoothening* residual roughness of core,
- focussing efficiency into +1st order: 6.9 % at 18 keV
- in principle, optical length >> 10 µm possible



MZP fabrication

Pulsed Laser Deposition (PLD) is a convenient method to grow alternating layers on a rotating glass fibre

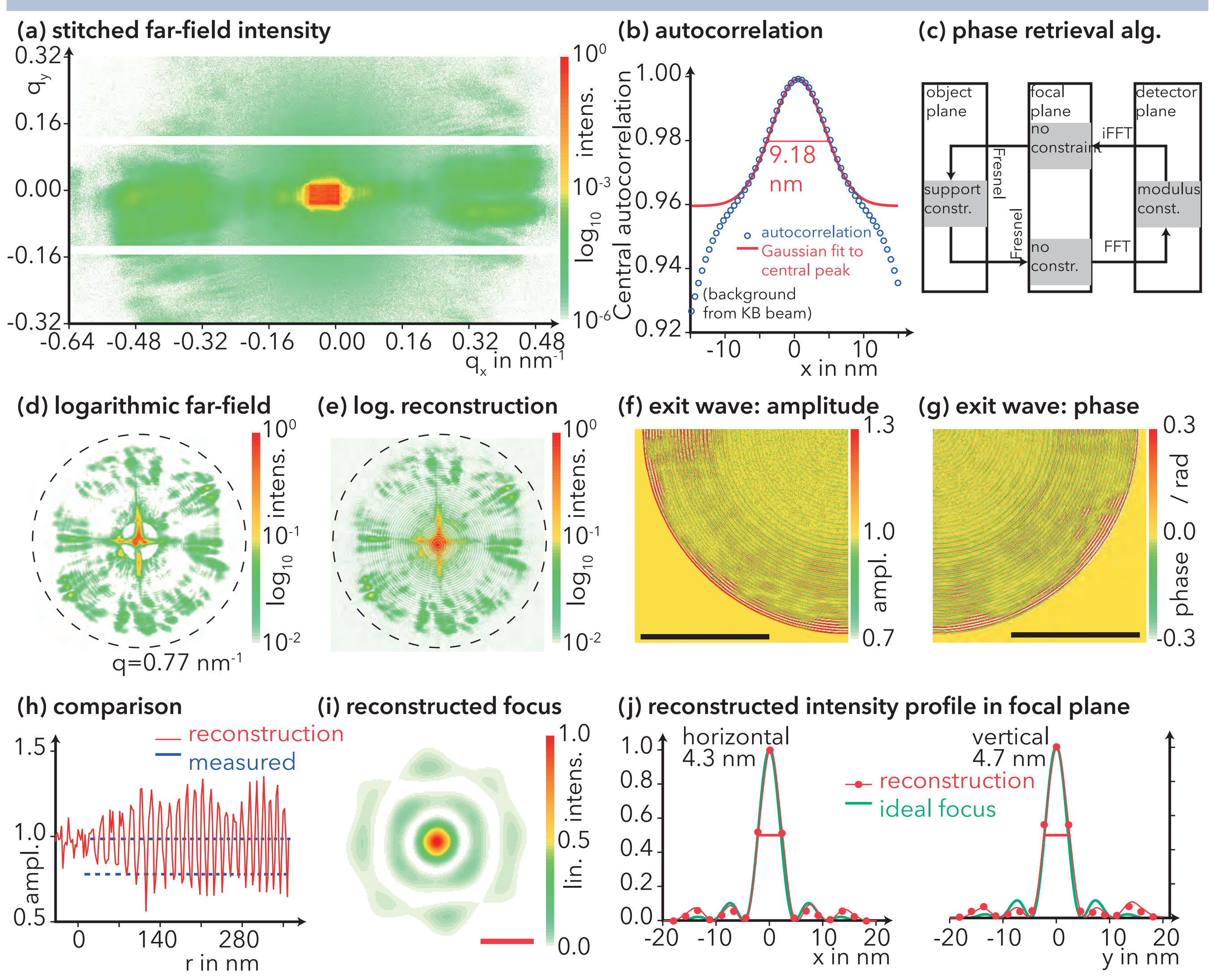
a using Focused Ion Beam (FIB) facility, the lens can be attached to a mount and cut to the desired optical length
b final polishing of the MZP with FIB
c high-resolution view showing 5 nm layers of high surface quality
d final polishing of the MZP with FIB
e detailed TEM image shows high quality layers, without cumulative roughness
f layer thicknesses closely match the zone plate law



Determining the focal spot size

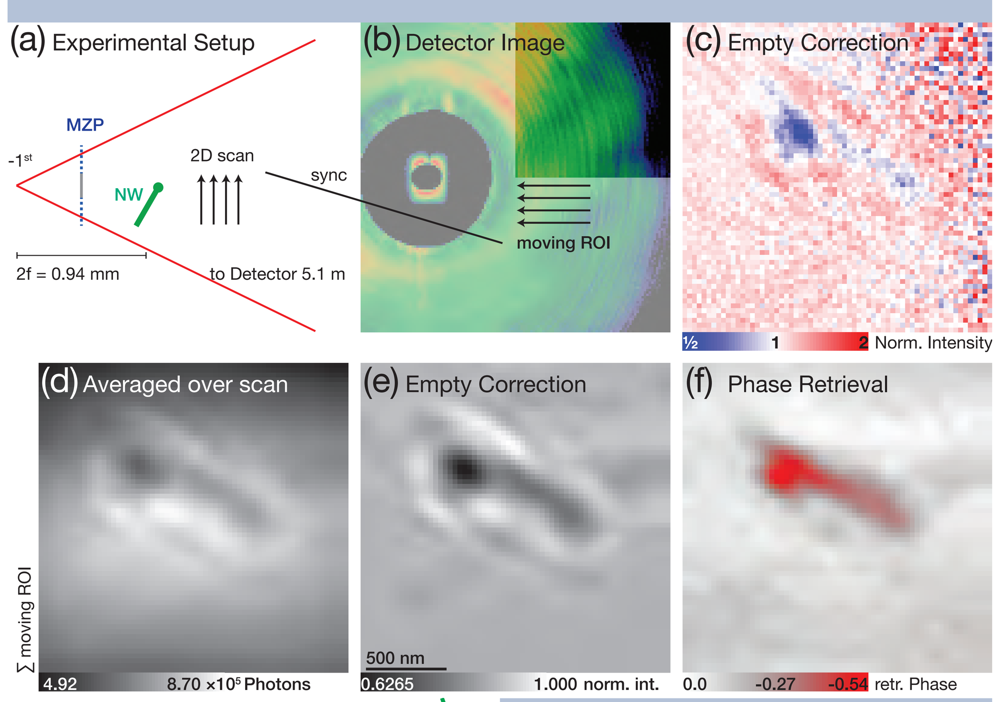
a far-field intensities (Pilatus detector, horizontally stitched); its auto-correlation yields ...
b a "typical length scale" of the diffraction strength; full width at half maximum of 9.18 nm corresponds to focus structures of 4.6 nm
c three-planes phase reconstruction scheme [H.M. Quiney et al., Nature Physics 2, 2006]
d log-scaled colour coded measured intensity (sCMOS detector)
e log-scaled colour coded reconstructed intensity
f reconstructed amplitude in lense plane,
g rekonstructed phase in lense plane; due to beam stop (necessary to protect detector from 0th order), zones inside central core appear
h reconstructed zones agree with measured layers
i reconstructed intensity in focal plane (interpolated)
j horizontal and vertical line profiles of i yield FWHMs of 4.3 nm × 4.7 nm, the so-far smallest 2D hard x-ray focus

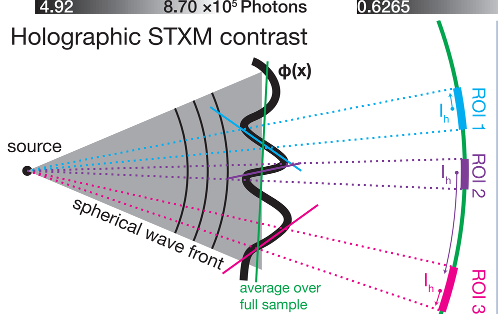
experiment at 7.9 keV; focal length 50 µm; W / Si
similar results at 13.8 keV; focal length 250 µm; W / ZrO_2



Holography

a 2D scan of semiconductor nano wire ...
b,c in diverging -1st MZP order shows holographic images ...
d averaged over 1647 positions, with detector ROI co-moving; no encoder / interferometer positions used yet
e empty corrected image to cancel shadow from beamstop and inhomogenuous illumination
f phase retrieval: holographic reconstruction plus Gerchberg-Saxton





Can we go further and get "differential phase contrast"-like data out of STXM scans?

Placed in a diverging order, the image appears in the holographic regime; for a small detector ROI we can compute the local "centre of mass/intensity". If the phase curvature is sufficiently small, the c.o.m. stays within the ROI and can be used for imaging – using classical STXM algorithms, see the next box on the right side ▶.

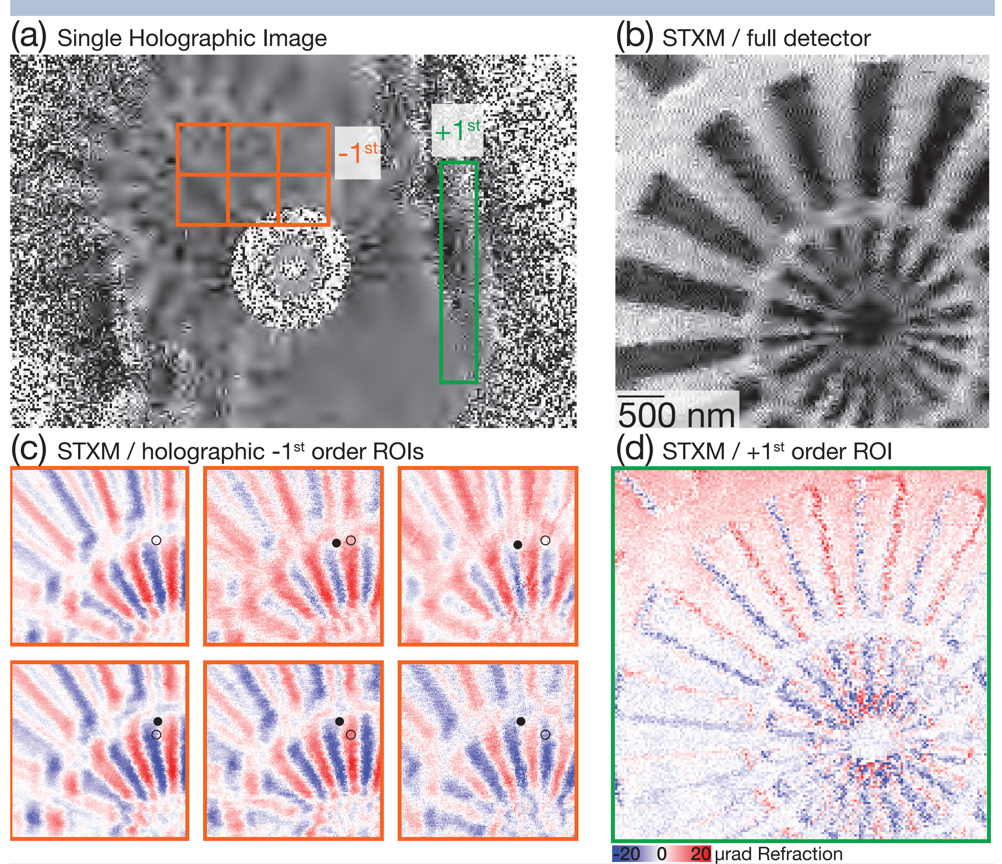
Imaging by scanning

A Siemens star test pattern was scanned laterally in the +1st focal plane.
a far-field showing a holographic image of the star; this is attributed to the divergent illumination of the -1st order.

Intensities $I(X,Y)$ are recorded for every scan position (x,y).
Differential phase contrast (horizontal) $I_h(x,y)$:

$$I_h(x,y) = \frac{\sum_{X,Y \in \mathrm{ROI}} X \cdot I(x,y;X,Y)}{\sum_{X,Y \in \mathrm{ROI}} I(x,y;X,Y)}$$

b shows this signal, summed over full detector,
c shows I_h only for orange detector ROIs,
d shows the signal for the green ROI.



- STXM in divergent illumination yields holographic images,
- STXM in +1st focale plane yields differential phase contrast,
- MZP orders can be sorted out by "Software-OSA".

References

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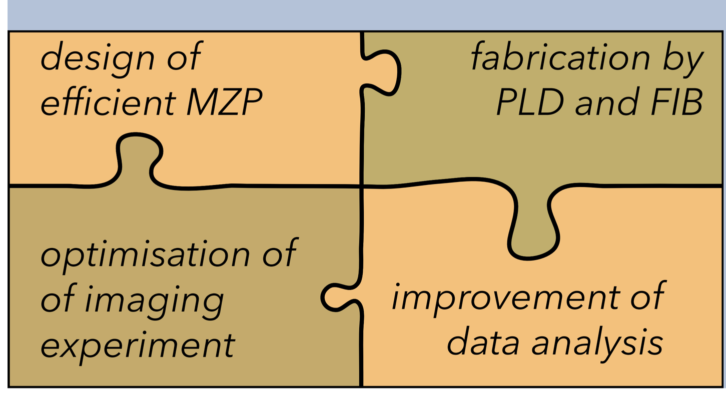
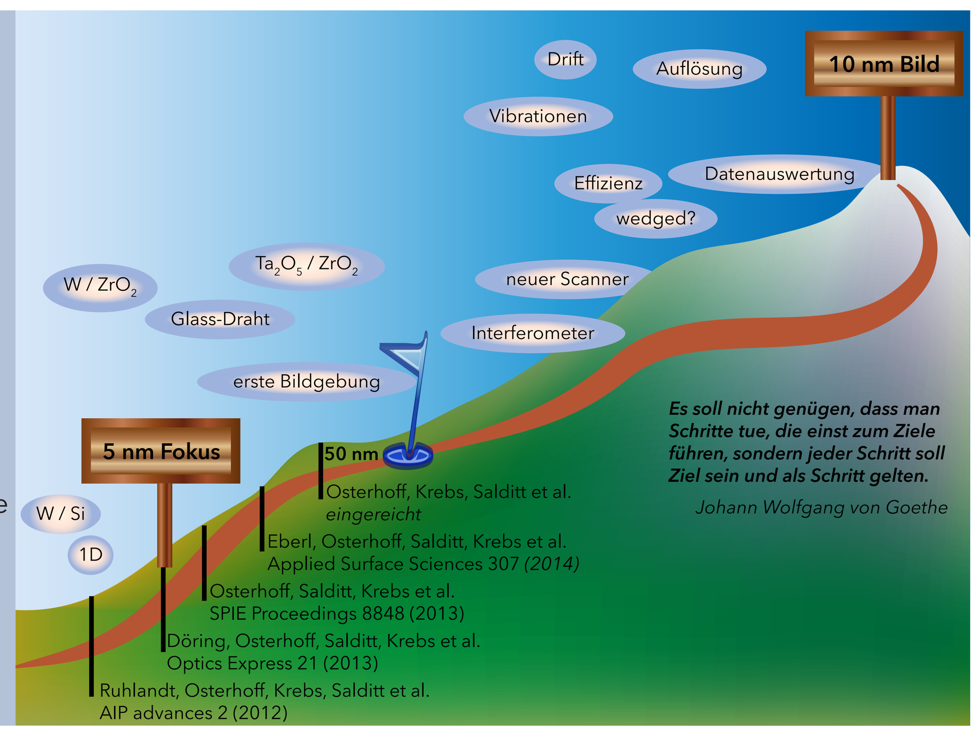
Future

We are envisioning hard x-ray imaging using MZPs with 10 nm resolution, addressing ...

drift	interferometric control in commissioning
vibrations	new sample tower / interferometry
slow scans	faster piezo scanner in commissioning
efficiency 6.9 %	thicker lenses (already got to 7 µm); optimised layer shape along optical axis, e.g. wedged



- understand and control volume diffraction / waveguiding effects
- check stability and endurance in FEL beam
- use for nano-diffraction, nano-fluorescence, nano-stimulation (e.g. XBIC)



dada: a web-based collaborative x-ray images visualisation and analysis tool

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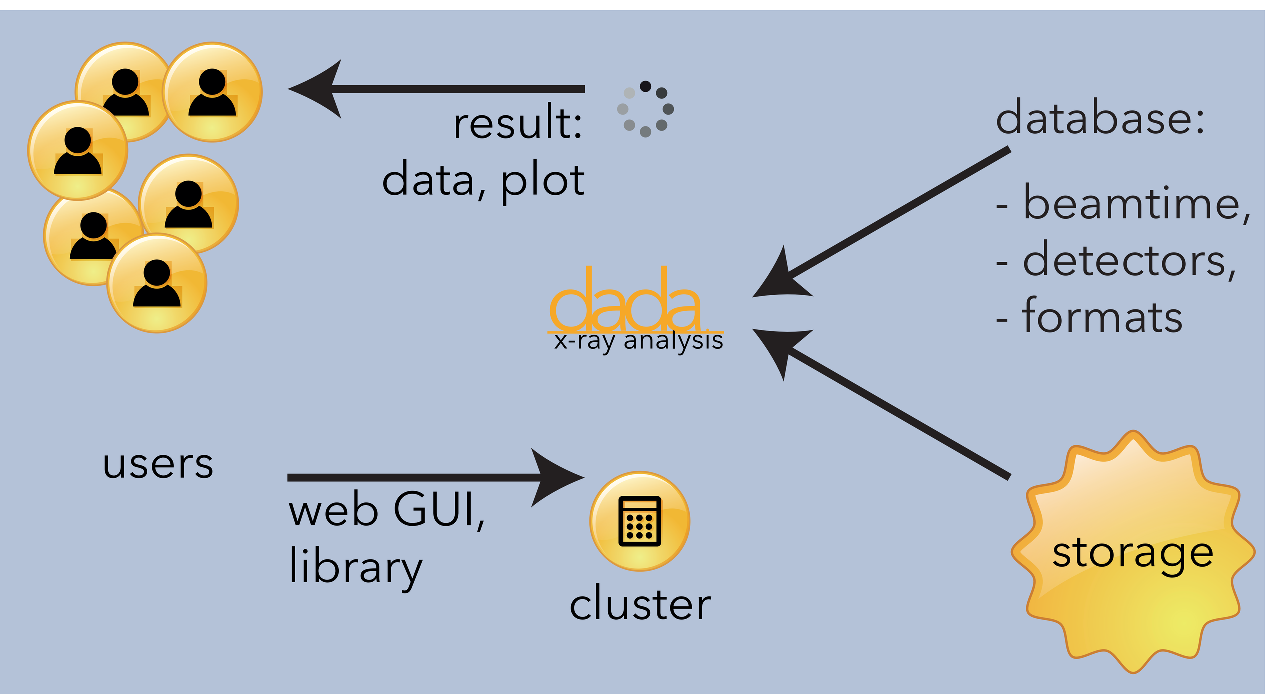
Motivation

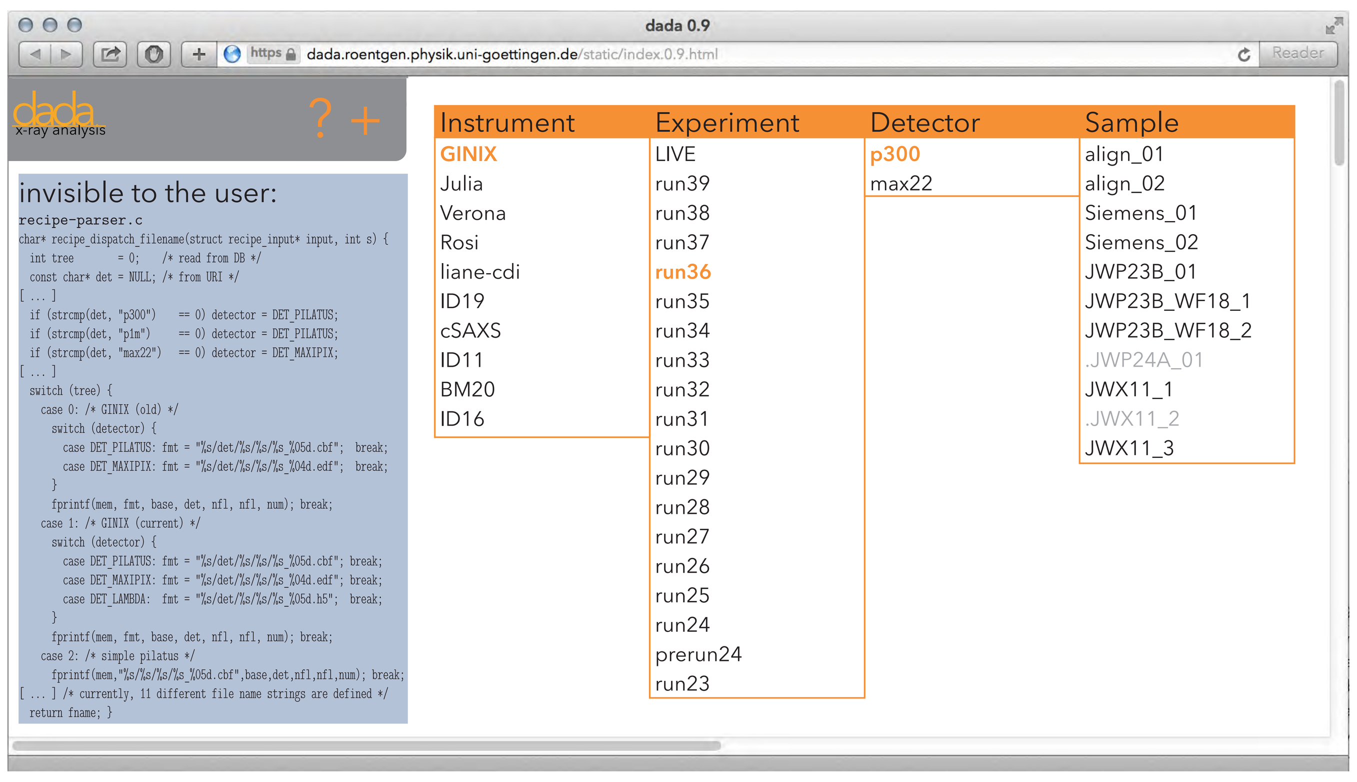
Challenges as university users of synchrotron / lab sources:

- different detectors / formats / compressions (changes even between beamtimes)
- different folder structure / file name formats (the famous %04d with varying 0's and 4's, **"the mess"**)
- Bachelor students come and go
- their need: "just show me that image!"
- often heard on the floor: "I got **this algorithm** from her, but the one from him is **newer**, but then I included **this piece of code** taken from someone else to open that image, but now I forgot the **value of alpha**, and ***tomorrow I have to print my thesis***."

Our idea

- centralised, unified **access** to (2D, x-ray detector) images
- standardised **algorithms**
- UI: **web-GUI**, Matlab **interface**, {C, C++, Python} libraries possible
- **no local copy** of data
- use **central** cluster
- **cached results** / **archive** by URL, ID
- **control** and **view** from *anywhere*, i.e., the internet
- **https** and **authentication**, fully transparent **proxy**





dada

data daemon:

- database of instruments, experiments, used detectors
- one implementation of folder structure / file names
- web-based GUI, export to PDF, import from Matlab, other libraries planned
- basic tasks:
  find that image!
  show that image!
  analyse those images!

Status

Detectors:
Pilatus (cbf, edf, tiff)
Maxipix (edf)
FReLoN (edf)
certain TIFFs
certain HDF5s

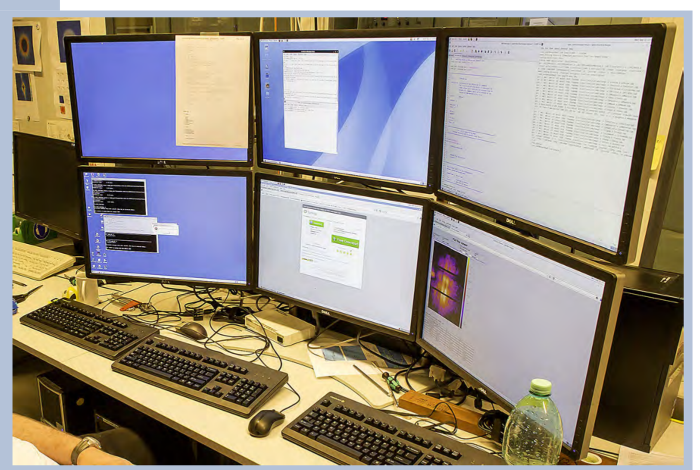
SPEC scans (currently, 1D)

Single image:
ROI, binning, summing, divide, subtract, movie, lin/log, colourbar, line profiles, export to png/pdf/Matlab

Composite and STXM
darkfield, differential phase

At the beamline

GINIX set-up @ P10 beamline



Control software: SPEC

Feedback from dada:

- counting on 2D detectors,
- centre-of-mass,
- peak width

Online **analysis**:

- print-outs including counting time and motor positions
- STXM measurements live from SPEC
- composite images (2D array of 2D images)
- clever combinations of ROI/binning/composite

Try it!

If you can see this text, the tablet is obviously absent.

Please visit

`http://dada.k-raum.org`

for a small demo.

Plans

Detectors:
advanced HDF5 routines, fluorescence detectors

2D SPEC scans

Single image:
radial / azimuthal profiles, fluorescence maps

Composite and STXM
more contrasts, combine with in-line mic

Behind the curtains

C back-end, lighttpd for HTTPS, authentification and proxy

web-GUI let's you browse images and adjust parameters

URI defines "module" (show, scan, stxm etc) and experiment / detector / sample / image number

query string defines modifiers: lin/log scale, colour map, ROI, STXM parameters etc

URI is transformed into JSON-encoded "recipe":

http:// dada / stxm / ID11/proposal/maxipix/nanowire1/42
? horz=161&vert=161&palette=bwr&scale=log ...

from short URI ↓ to JSON* recipe ...

```
{
"_type":          "stxm",
"_version":       "v.01",
"input": {
  "instrument":   "ID11",
  "experiment":   "hc1182",
  "detector":     "maxipix",
  "sample":       "nanowire1",
  "number":       42,
  "dimensions":   2,
  "size":         [ 161, 161 ]},
"roi": {
  "x":            700,
  "y":            166,
  "w":             50,
  "h":             50 },
"colour": {
  "scale":        "log",
  "palette":      "bwr" },
"output":         {
  "format":       "pdf" }
}
```

* JavaScript Object Notation

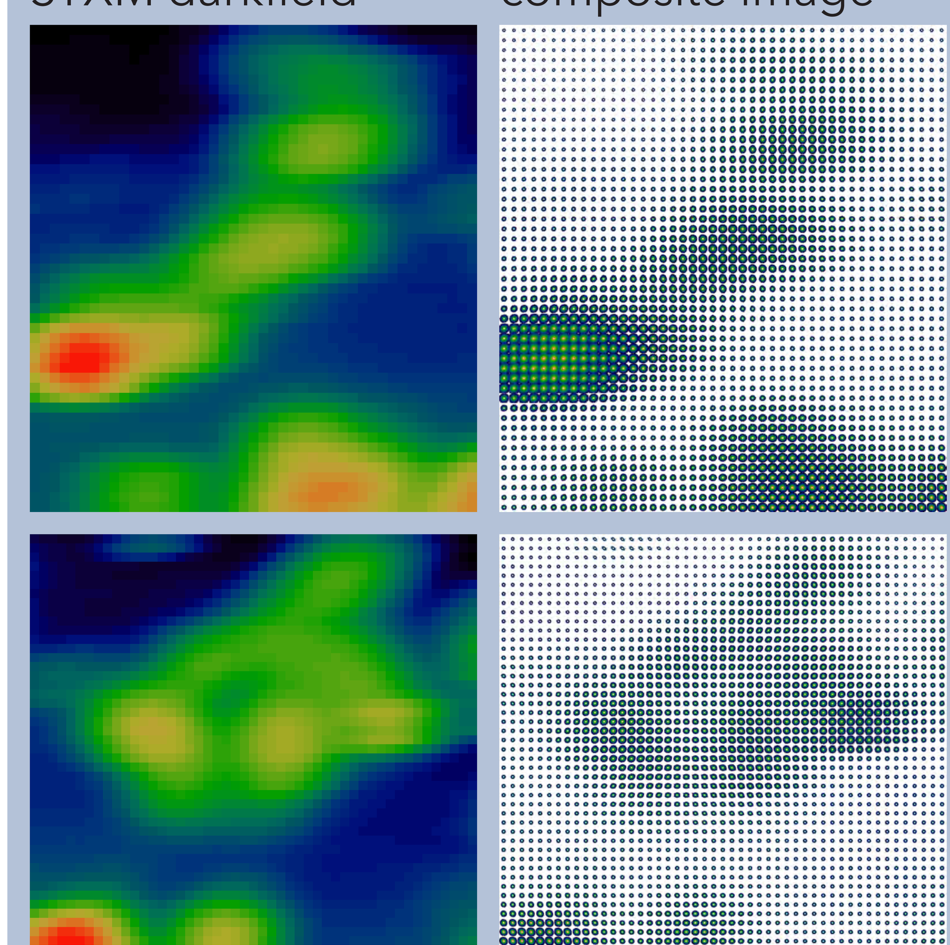
hash(JSON): look-up in cache database (sqlite3)

if cached: return { image, processed data, meta data etc. }

otherwise: process, calculate, render, cache, serve

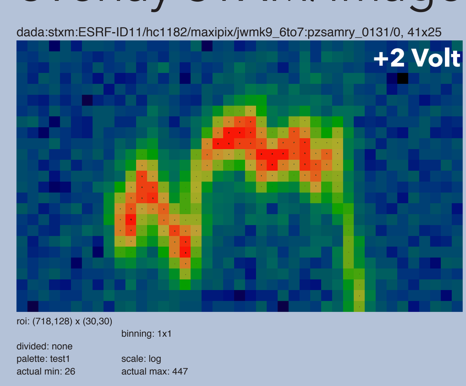
Examples

STXM darkfield | composite image



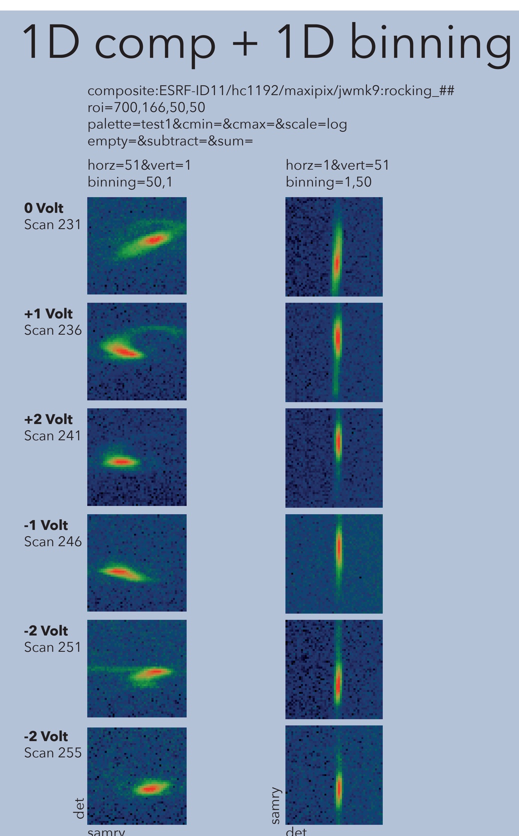
STXM darkfield contrast together with composite images (2D × 2D) during alignment of hMSC cells in nano-diffraction experiment
(M. Bernhardt, unpublished)

overlay STXM/image



combining STXM signal with detector images per position to measure strain in nanowire
(J. Wallentin, unpublished)

1D comp + 1D binning



horizontal composite of vertically binned images (and vice versa) to visualise rocking scans of *in operando* contacted nanowire; here for different bias voltages
(J. Wallentin, unpublished)