The importance of Shear in sliding CDW observed by Xfel source

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Karina Kazarian (LPS)
U. Boesenberg *(E-XFEL Hamburg)*

Transformations of Correlated Electronic States by Electric or Optical Impacts. International research school and workshop IMPACT – 2024

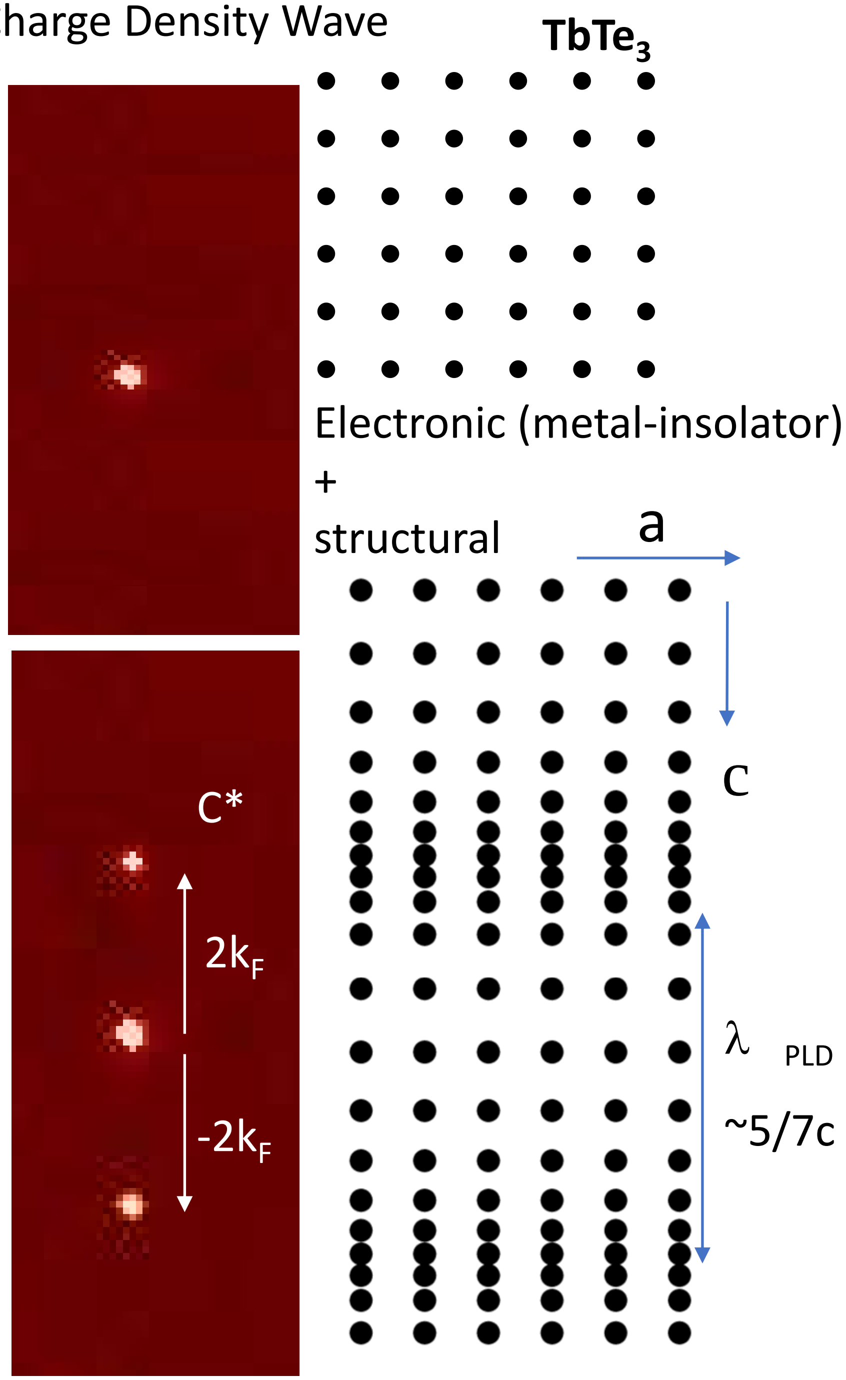
August 19 – 31, 2024
Cargèse, France

Overview Accommodation Room Reservation Transportation Venue and location Program Registration and conference fee

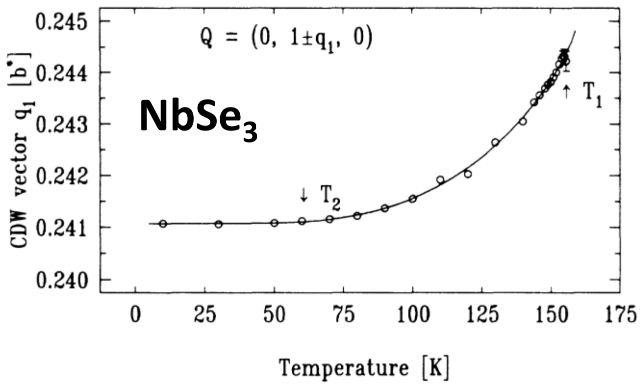
Practical information Abstract submission.

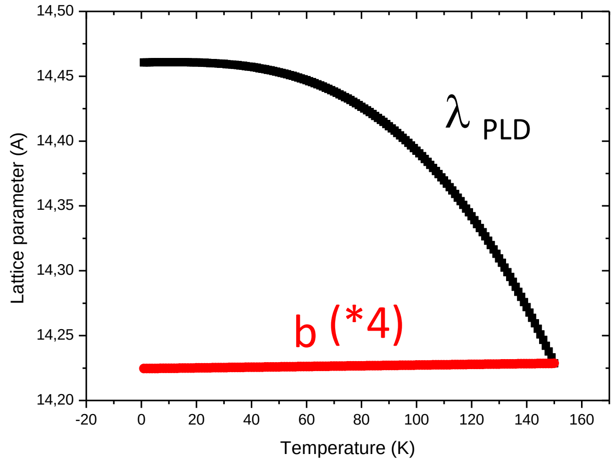
Incommensurate CDW is sensitive to numerous excitations

Charge Density Wave



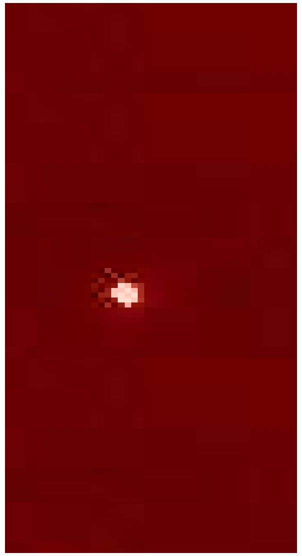
1. Temperature

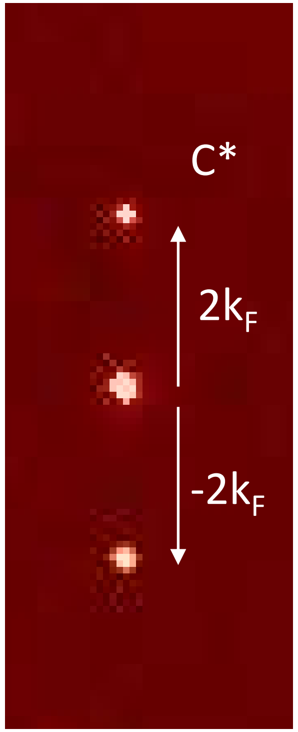




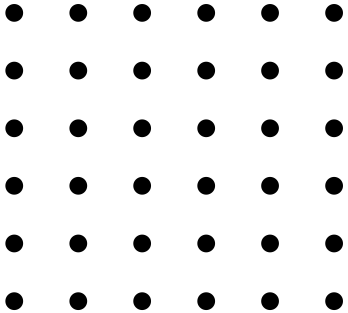
A.H. Moudden, PRL 1990

Charge Density Wave

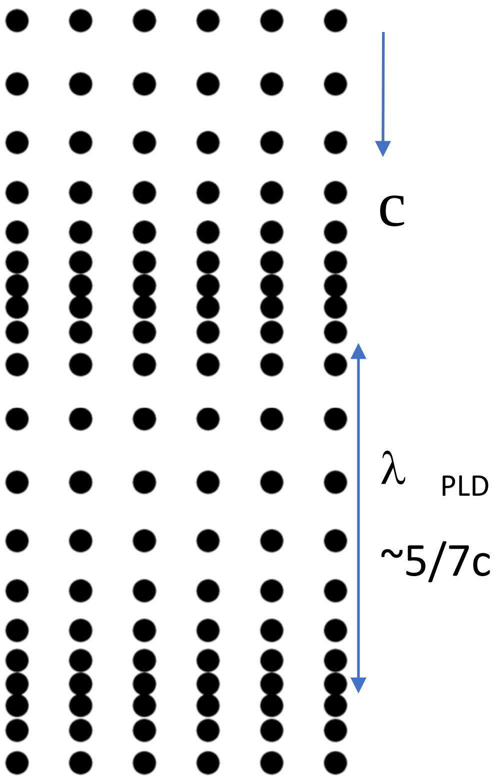




$TbTe_3$



Electronic (metal-insolator)
+
structural



A.H. Moudden, PRL 1990

Incommensurate CDW is sensitive to numerous excitations

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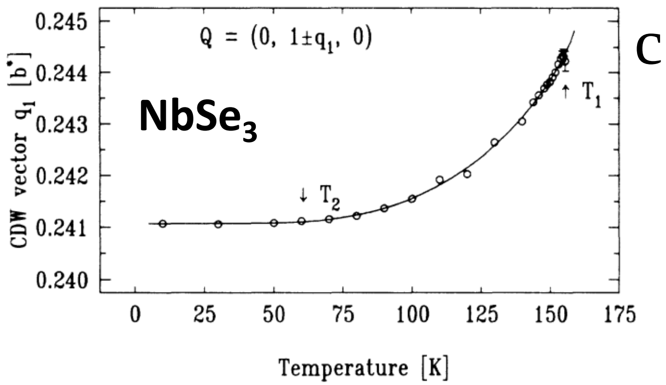
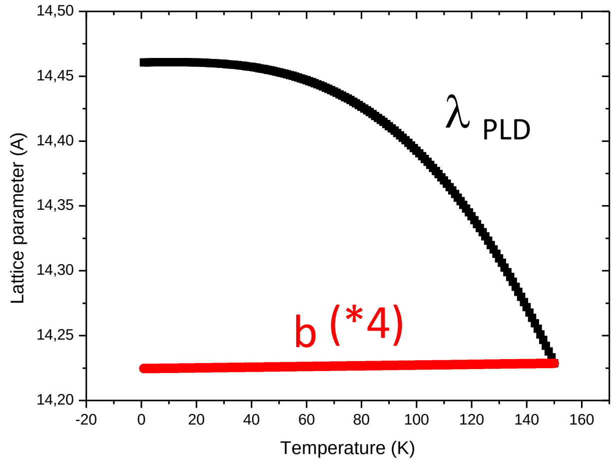
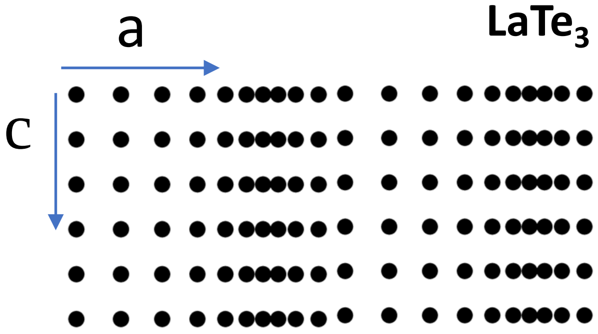
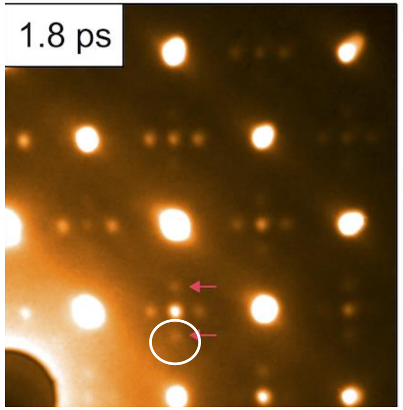




2. Ultra short light pulse

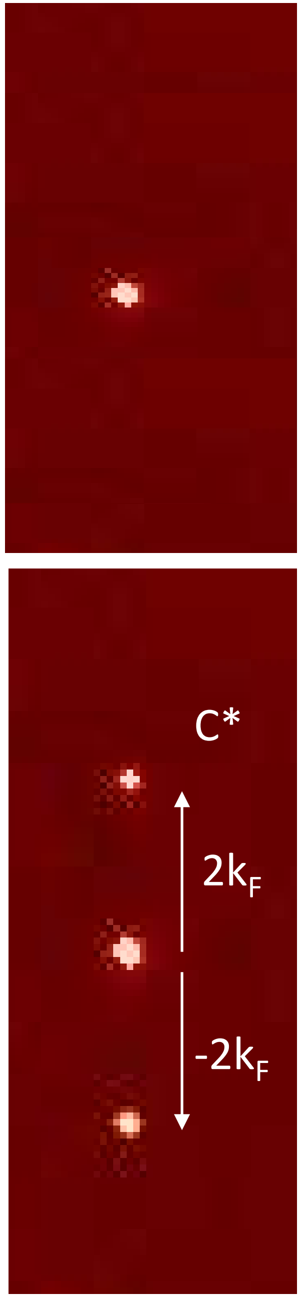


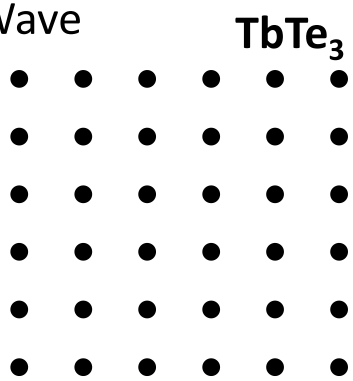


A. Kogar et al., Nat. Phys. **16**, 159 (2

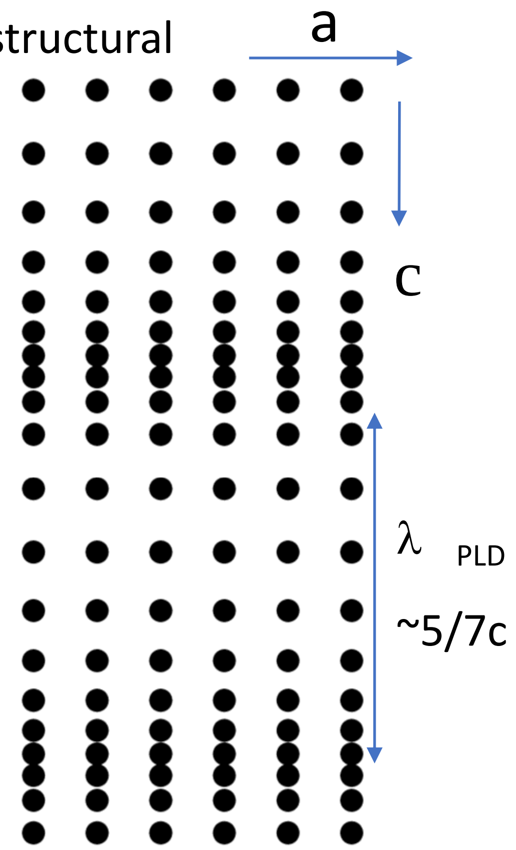
Charge Density Wave

Incommensurate CDW is sensitive to numerous excitations



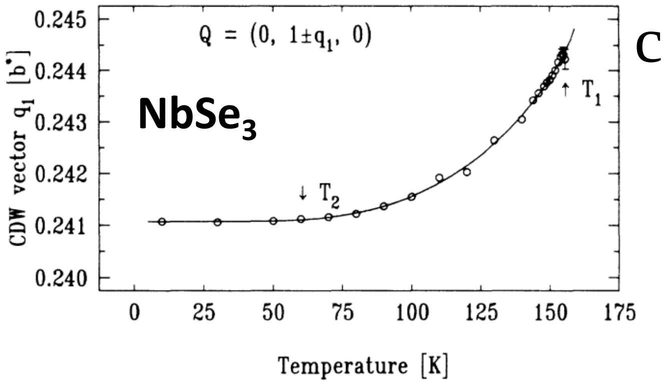


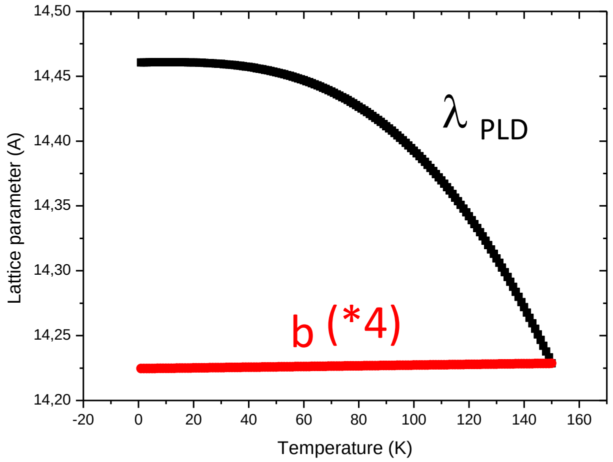
Electronic (metal-insolator)
+
structural



A.H. Moudden, PRL 1990

1. Temperature





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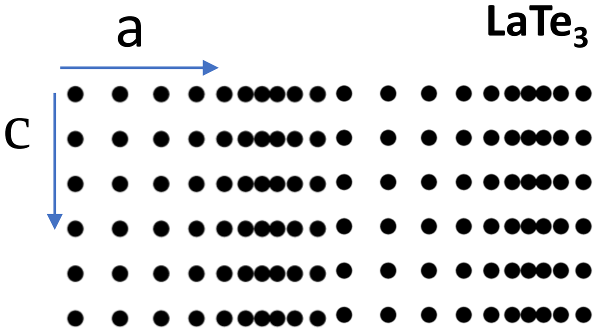
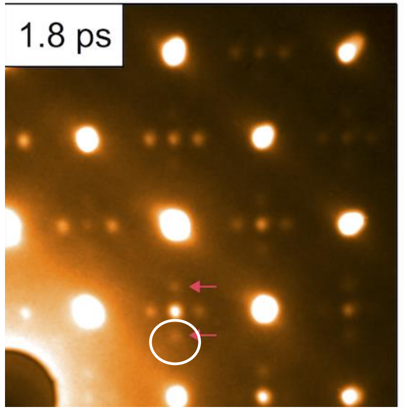
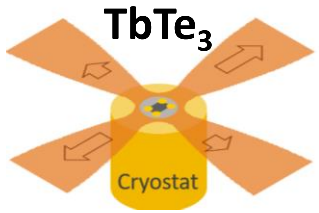
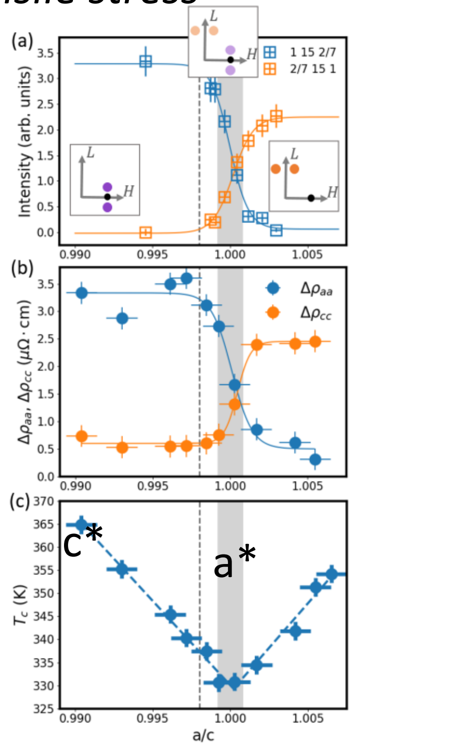




A. Kogar et al., Nat. Phys. **16**, 159 (2

3. CDW tuned by biaxial tensile stress





a/c

(V. Jacques presentation
Last week)

A. Gallo-Frantz *et al.*, Nat. Comm.,

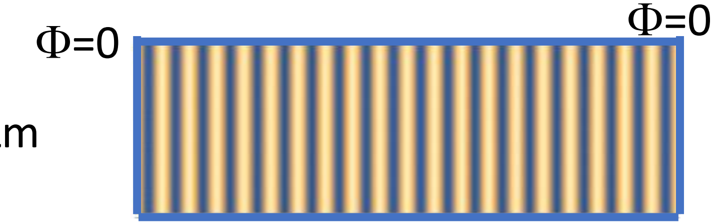
4. External currents

a. small current: strong lateral surface pinning

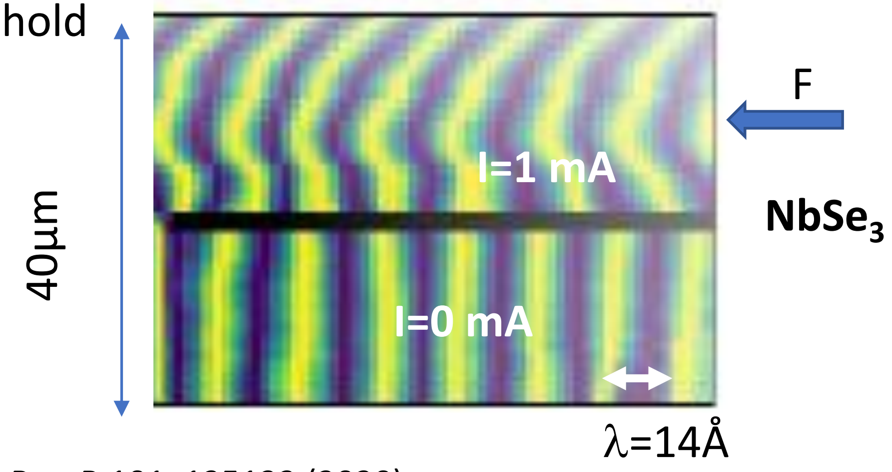
Curvature of wave fronts (shear strain)

Curvature at the nm scale, over tens of µm

Fast scanning diffraction (ID01 ESRF)



below threshold



E. Bellec et al., Phys. Rev. B 101, 125122 (2020)

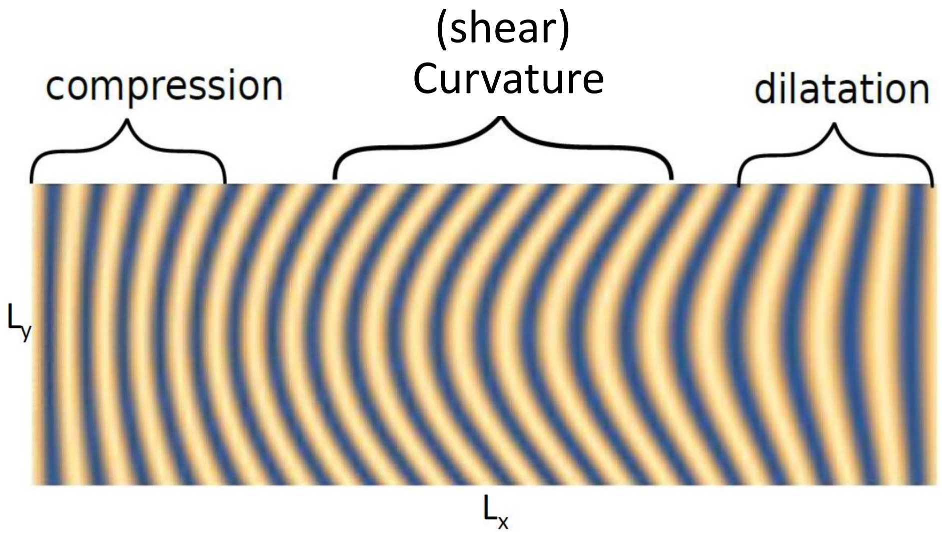
$$2\left(c_x^2\frac{\partial^2\phi}{\partial x^2}+c_y^2\frac{\partial^2\phi}{\partial y^2}+c_z^2\frac{\partial^2\phi}{\partial z^2}\right)-\omega_0^2\phi\approx\eta E$$

with the Dirichlet conditions:

$$\phi\left(\pm\frac{L_x'}{2},y',z'\right)=\phi\left(x',\pm\frac{L_y'}{2},z'\right)=\phi\left(x',y',\pm\frac{L_z'}{2}\right)=0$$

2D guitar…

2 types of deformations: longitudinal/transverse



Green function + Charge image method

First order:

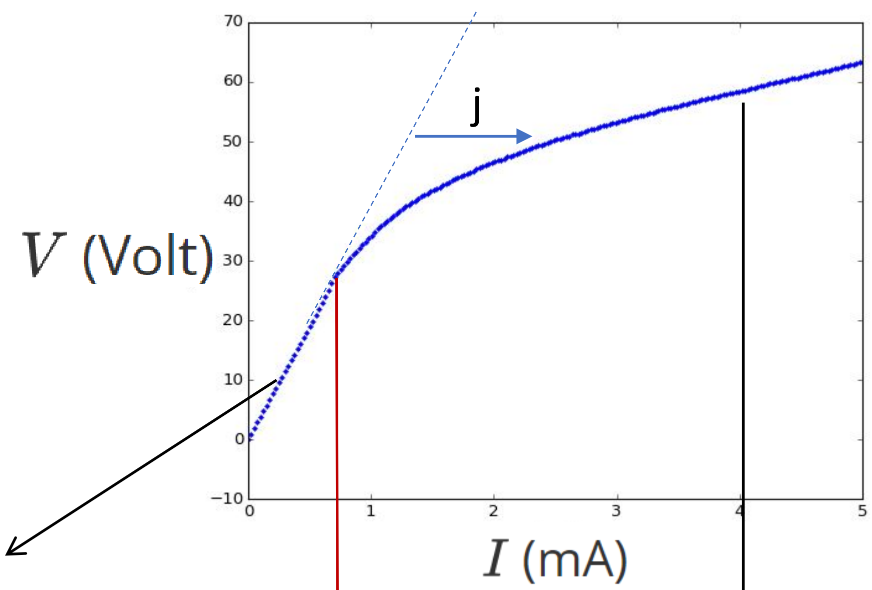
$$\phi(\vec{r})\propto -E\eta\beta\cos(\pi\frac{x}{L_x})\cos(\pi\frac{y}{L_y})\cos(\pi\frac{z}{L_z})$$

$$\beta=\frac{1}{\frac{c_x^2}{L_x^2}+\frac{c_y^2}{L_y^2}+\frac{c_z^2}{L_z^2}+\frac{\omega_0^2}{2\pi^2}}$$

E. Bellec et al., Eur. Phys. J. B (2020) 93: 165

b. **Above the treshold: Incommensurate Charge Density Wave may *slide***

I-V characteristic



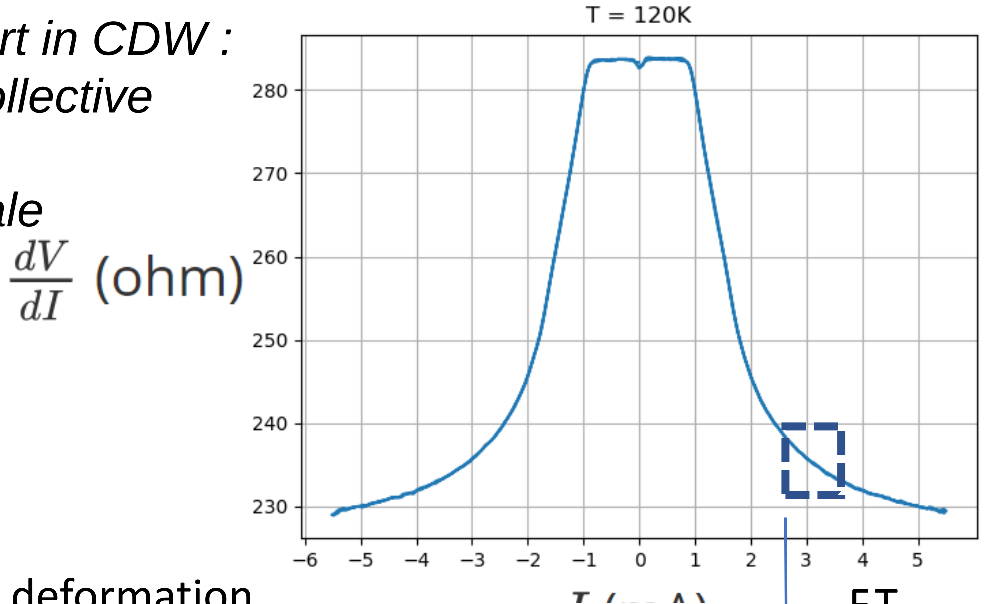
Ohm's law

Threshold current I_s

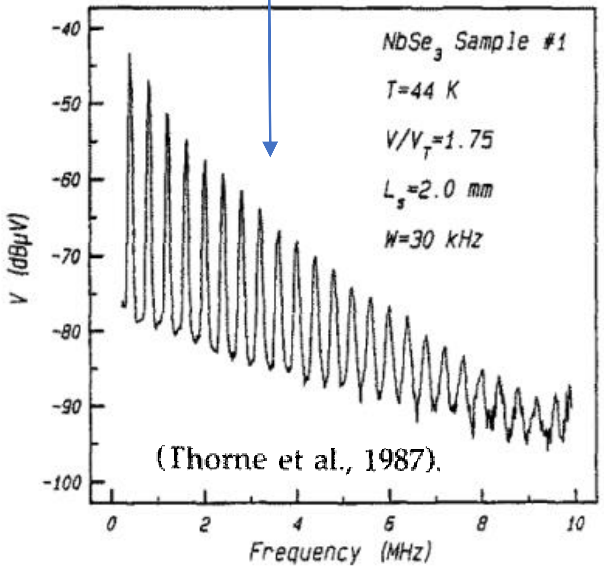
An excess of current

The charge transport in CDW : it is a pulsed and collective mode which occurs on macroscopic scale

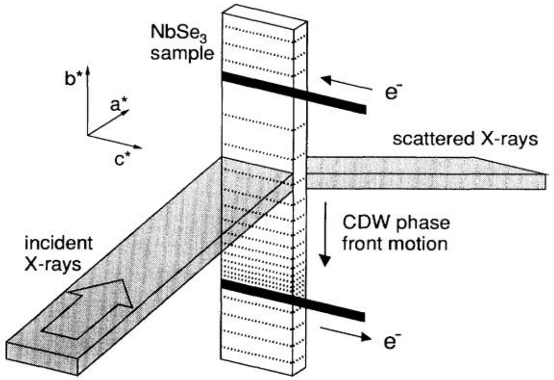
Differential resistivity as function of current in $NbSe_3$



F.T.



Longitudinal deformation (compression/dilatation)

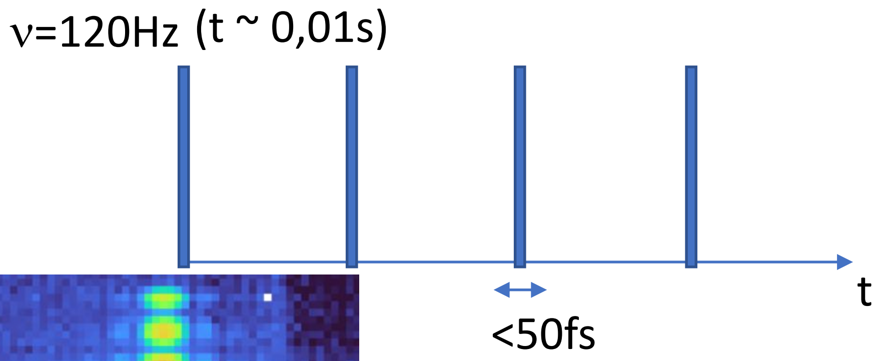


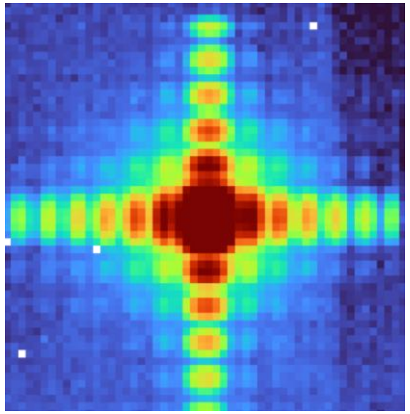
D. DiCarlo *et al.*, Phys. Rev. Lett. **70**, 845 (1993)
H. Requardt *et al.*, Phys. Rev. Lett. **80**, 5631 (1998)

Nonlinearity I-V directly linked to the CDW

Depining process (usual in condensed matter):
Magnetic domain walls motion under B
Dislocations nucleation under mechanical strain
Vortices motion in superconductors with E

XFEl source to obtain a global picture of sliding CDW





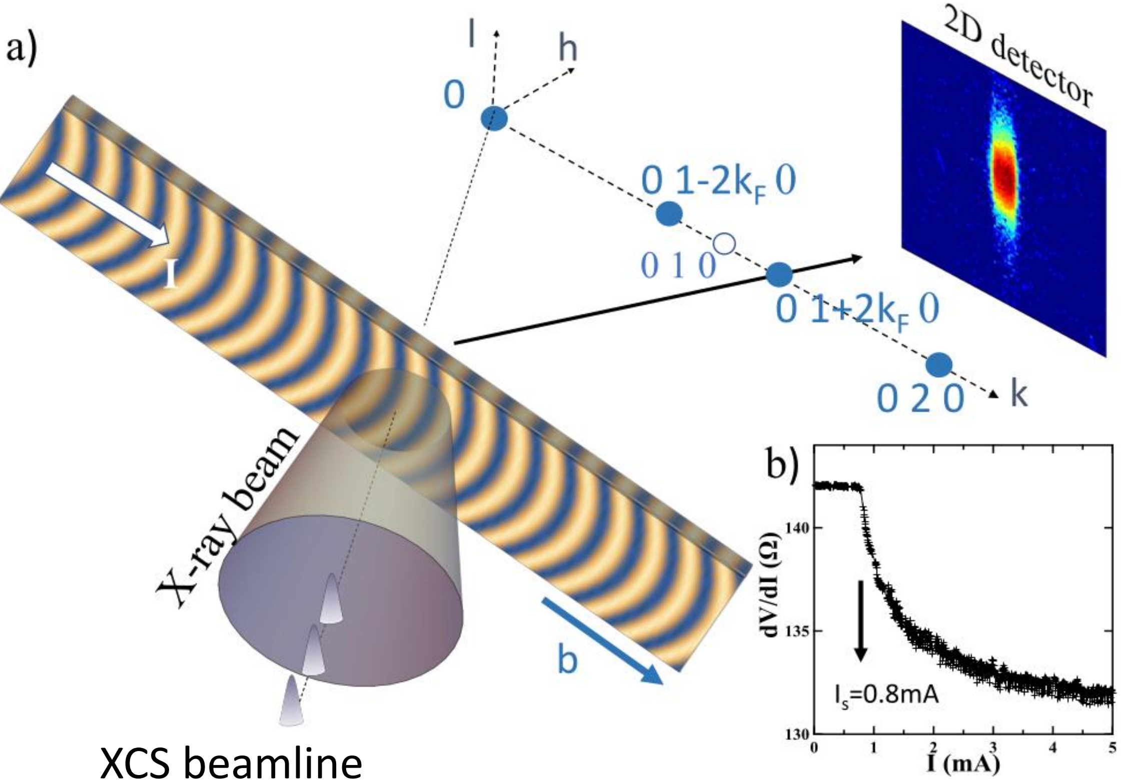
Large and fully coherent beam

Slit diffraction 10µm*10µm

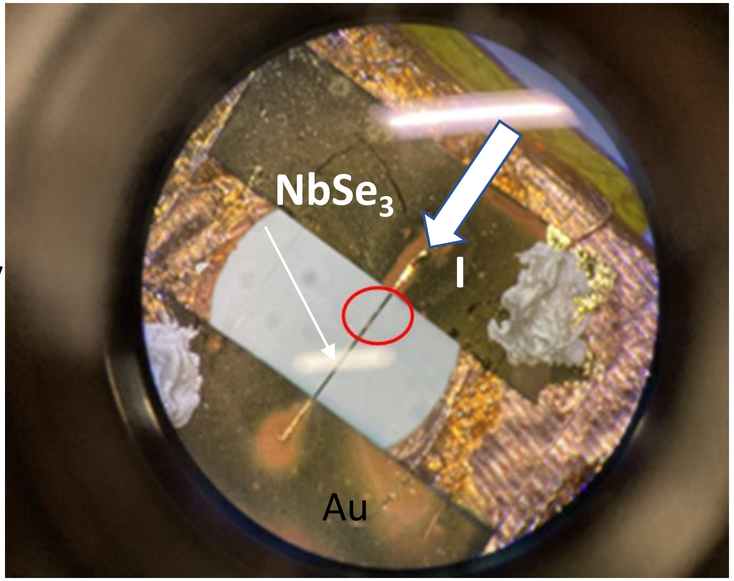
Sample width 40µm
Sample thickness: 0.5µm
Sample-det=8m
Beam size 35µm
9.5keV

High brillance

Stable satellite intensity from pulse to pulse



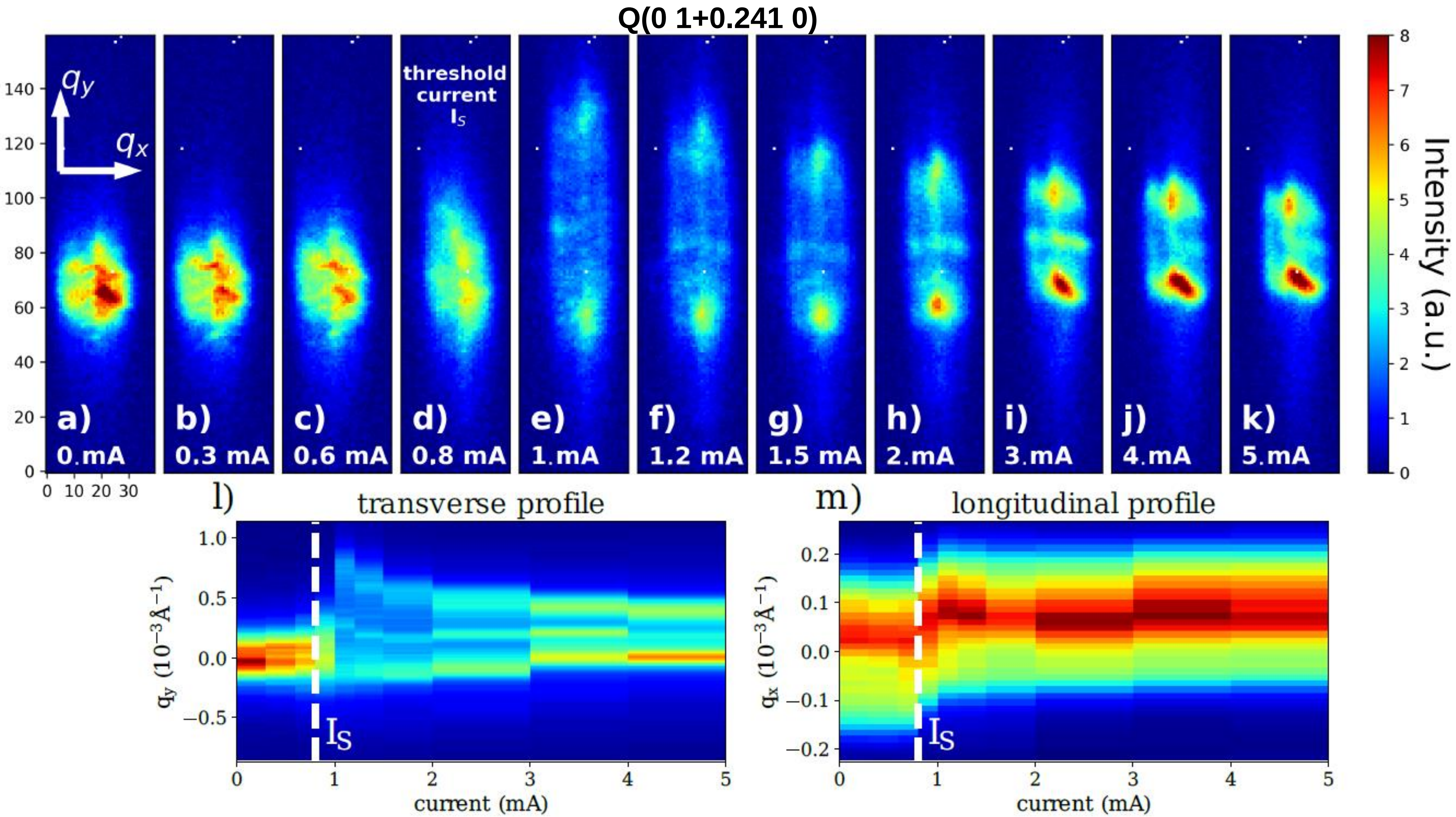
XCS beamline



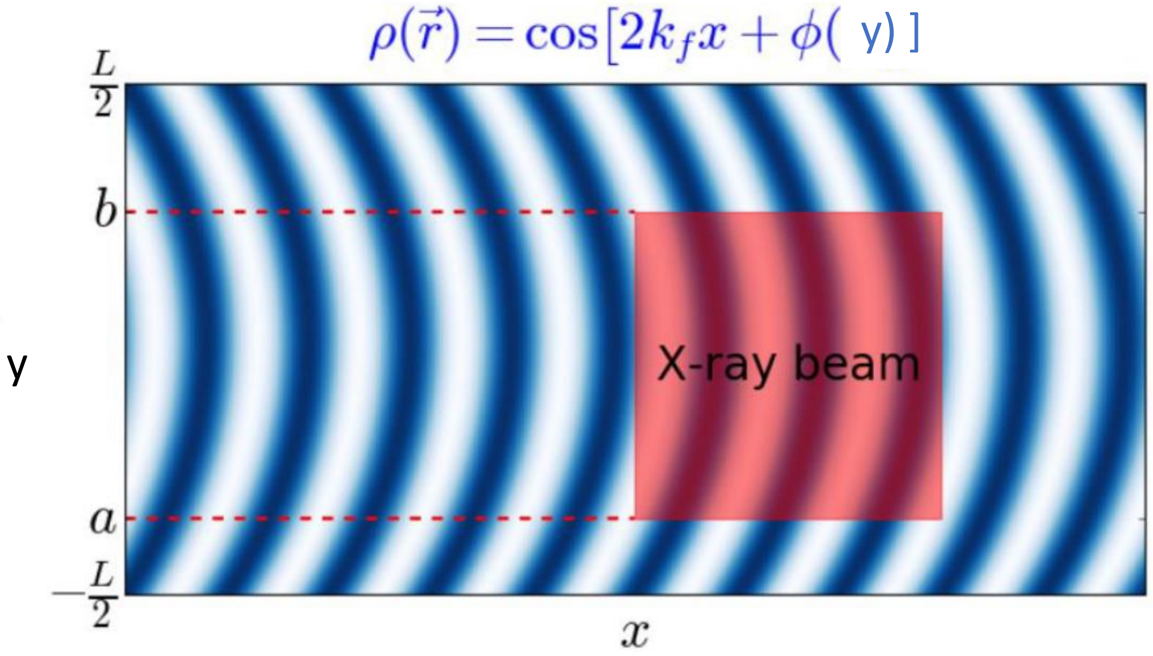
T=80k

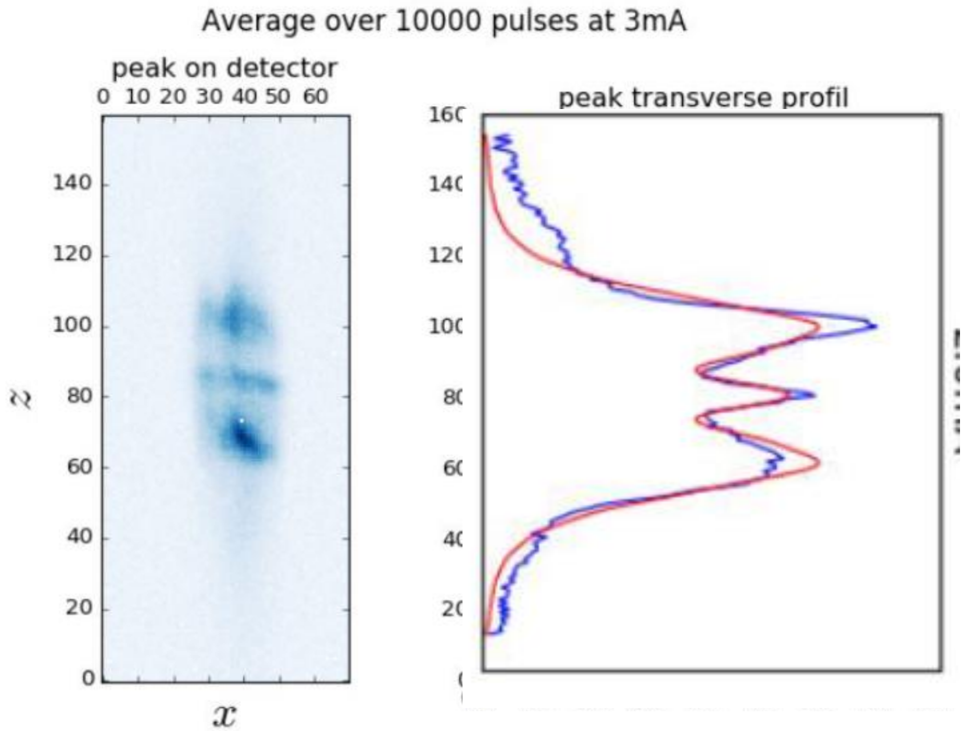
(T_c=140K)

A. Sinchenko



Diffraction patterns versus current. (A) to (K) Integrated rocking curve of the (0 1+q_S 0) satellite reflection associated to the CDW in $NbSe_3$ with increasing currents. The threshold current I_S=0.8mA is indicated in (D).





Where $\rho(\vec{r})$ is the CDW charge density and $\phi(z) = -\frac{F}{2}(z - \frac{L}{2})(z + \frac{L}{2})$.

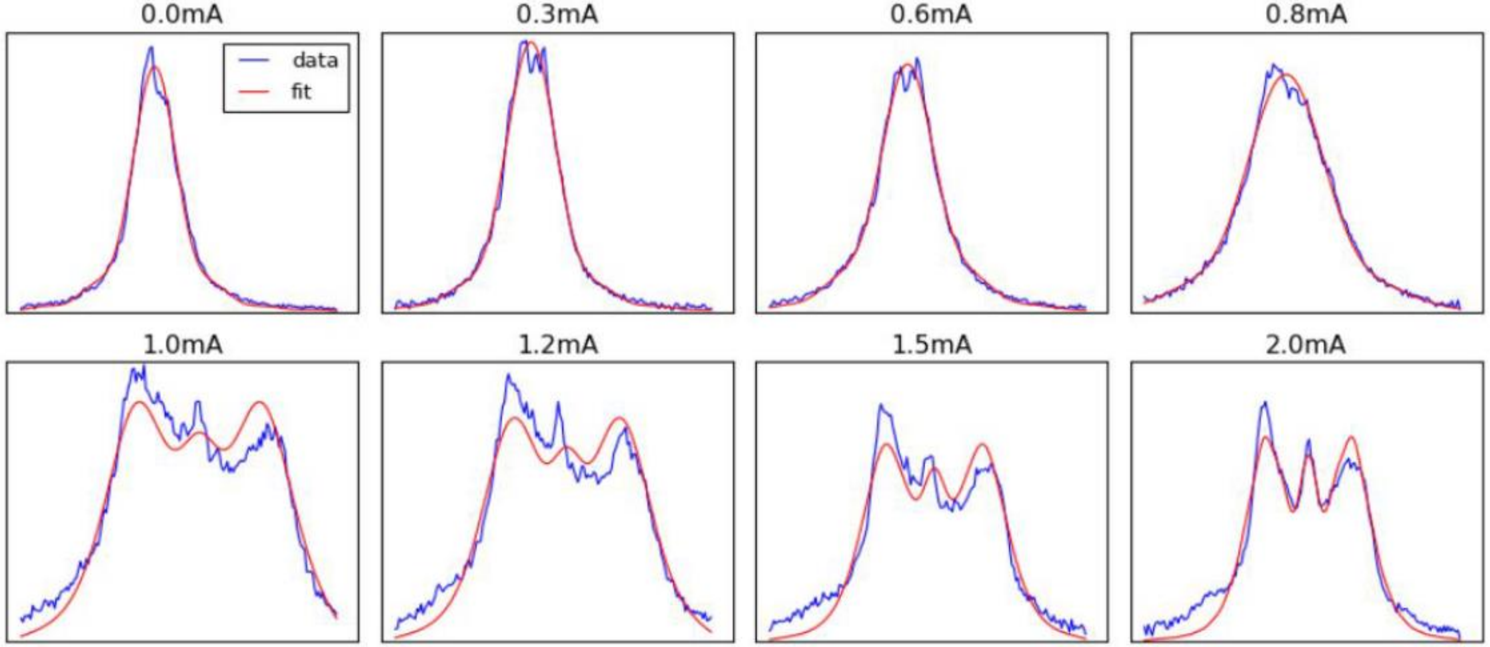
$$fit_{first\ try}(q_z) = |A_{fit}(q_z)|^2 = \frac{\pi C}{2F}\left|\text{erfi}\left[\frac{(1+i)(aF-q_z)}{2\sqrt{F}}\right] - \text{erfi}\left[\frac{(1+i)(bF-q_z)}{2\sqrt{F}}\right]\right|^2$$

where erfi is the imaginary error function $\text{erfi}(z) = \frac{\text{erf}(iz)}{i}$.

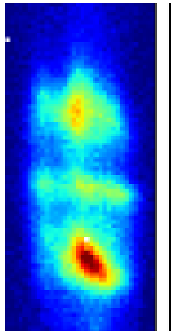
$$fit_{second\ try}(q_z) = fit_{first\ try}(\alpha q_z)$$

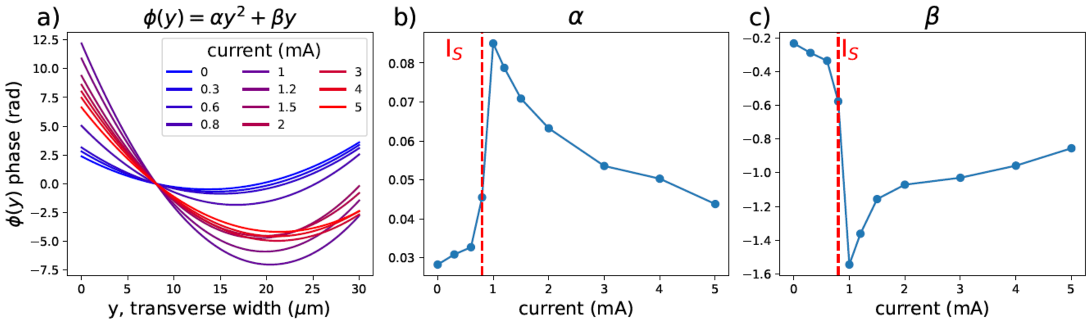
$$fit_{p_1,p_2,p_3,p_4,p_5}(q_z) = fit_{second\ try;p_1,p_2,p_3,p_4}(q_z) \circledast Gauss(q_z, p_5)$$

Fit considering a quadratic phase $\phi(y) = \alpha y^2 + \beta y$



Impossible
to fit the assymetry…





Phase retrieval: Genetic algorithm called Differential-Evolution (DE).

Stochastic process and iterative method: efficient for discontinuous or noisy case (not a gradient method)

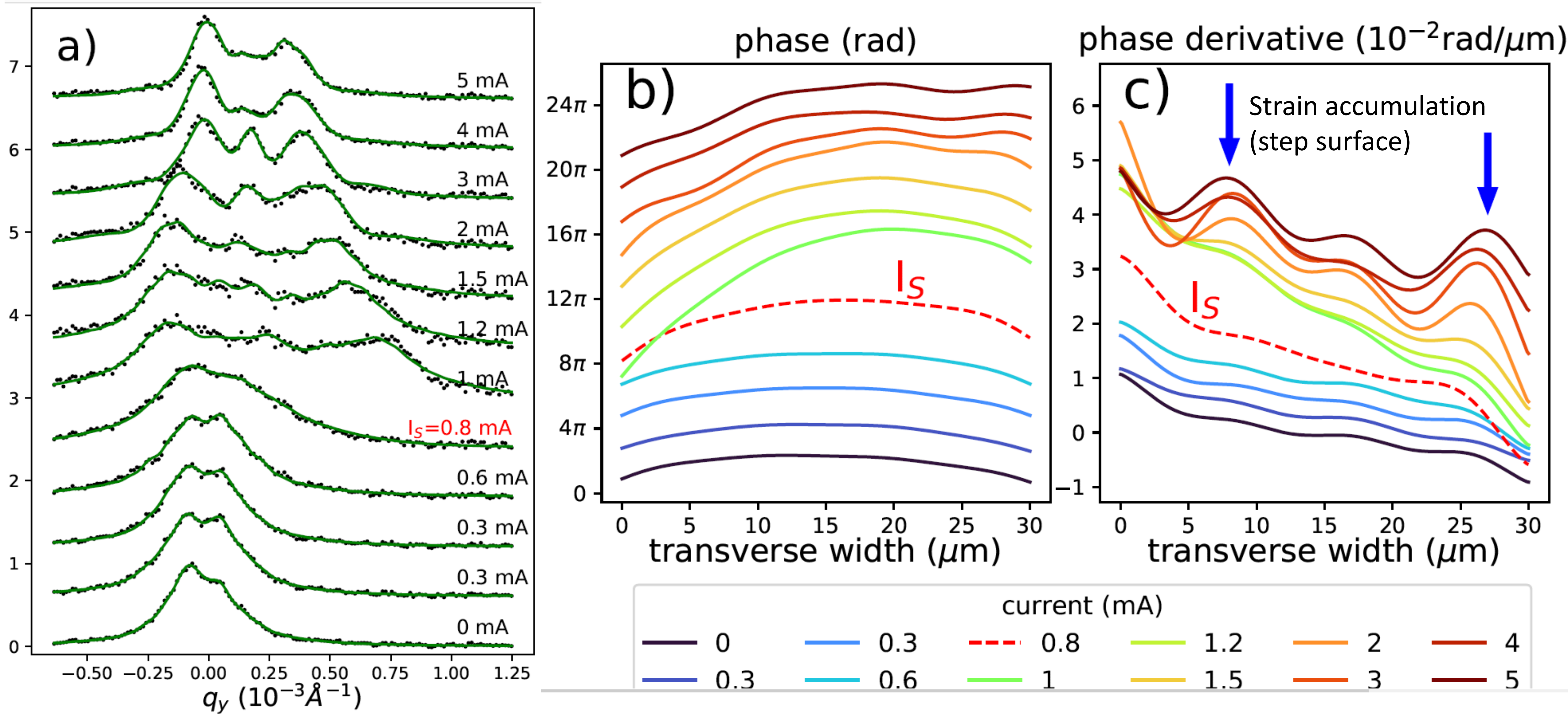
$$\phi(y) = c_1 \cos(\pi \frac{y}{L_y}) + \sum_{n=2}^{6} [c_n \cos(n\pi \frac{y}{L_y}) + s_n \sin(n\pi \frac{y}{L_y})] + \alpha y$$

R. Storn and K. Price, Journal of global optimization 11, 341 (1997).
M. K. M.Wormington Matthew, Panaccione Charles and
B. D. Keith Phil. Trans. R.Soc. **A.357**, 2827 (1999) (1999).
S. Das and P. N. Suganthan, 15, 4 (2010).

Elastic model:

$$\phi(\vec{r}) \propto -E\eta\beta \cos(\pi \frac{x}{L_x}) \cos(\pi \frac{y}{L_y}) \cos(\pi \frac{z}{L_z})$$

P. Wzietek



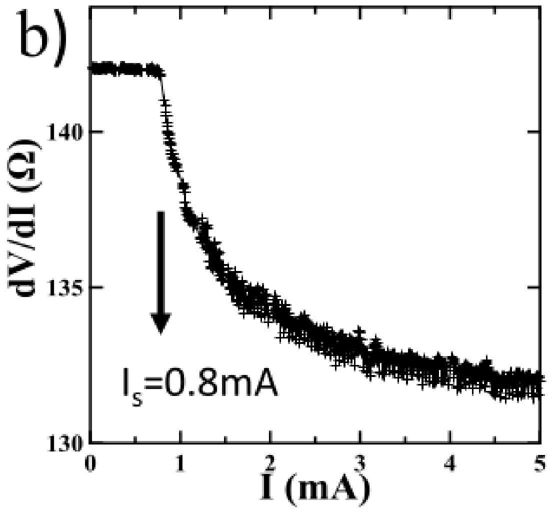
Shear component:

$$e_{xy} = e_{yx} = -\frac{1}{2}\frac{1}{q_s}\frac{\partial \phi}{\partial y}$$

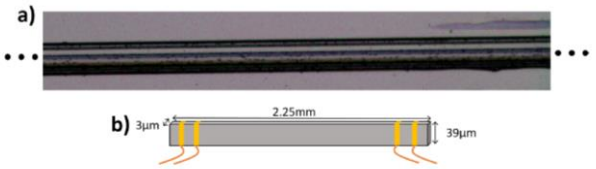
$\Phi(y) \sim (y-l_y/2)(y+l_y/2)$

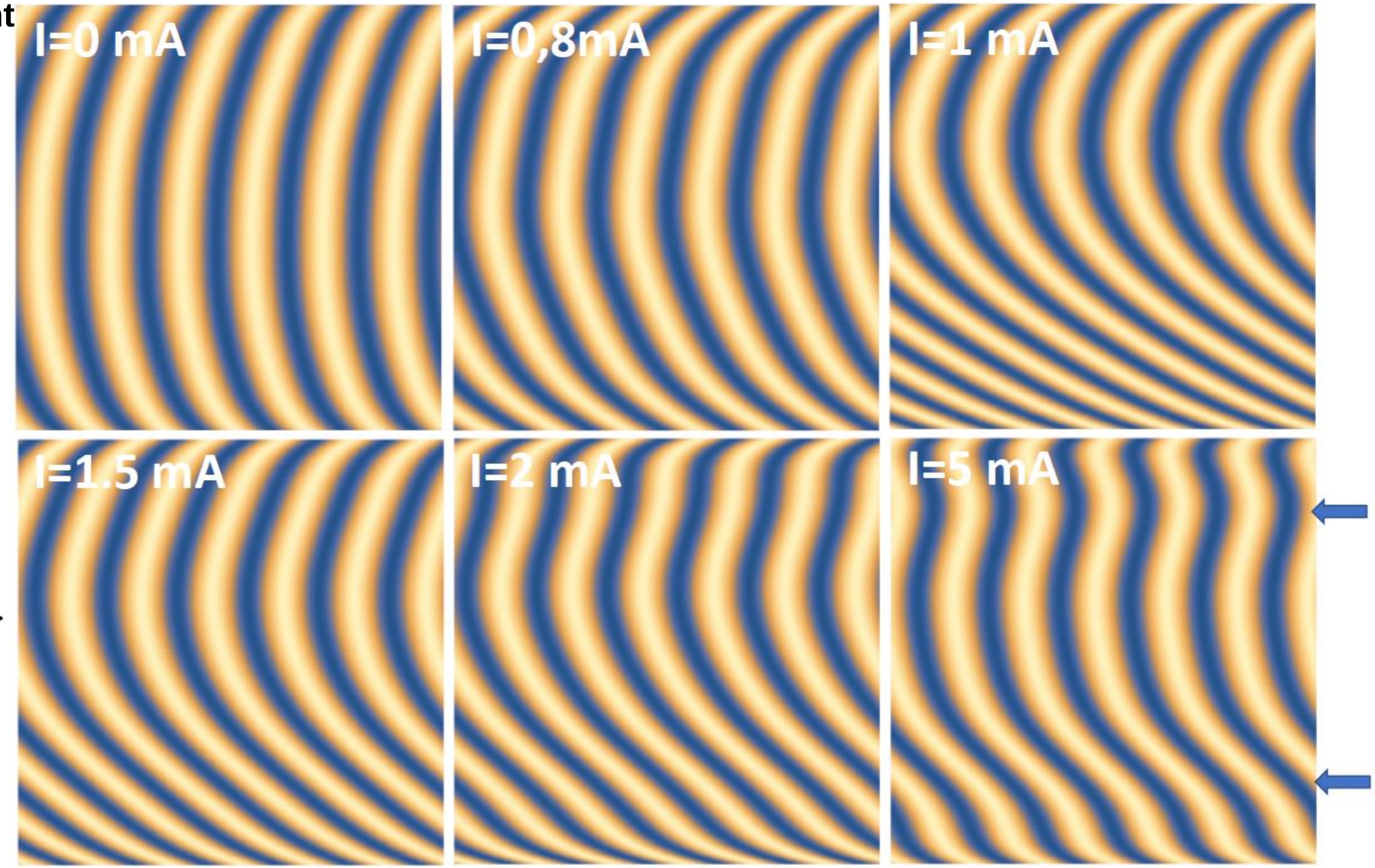
$\Phi'(y) \sim 2y$

CDW state versus current



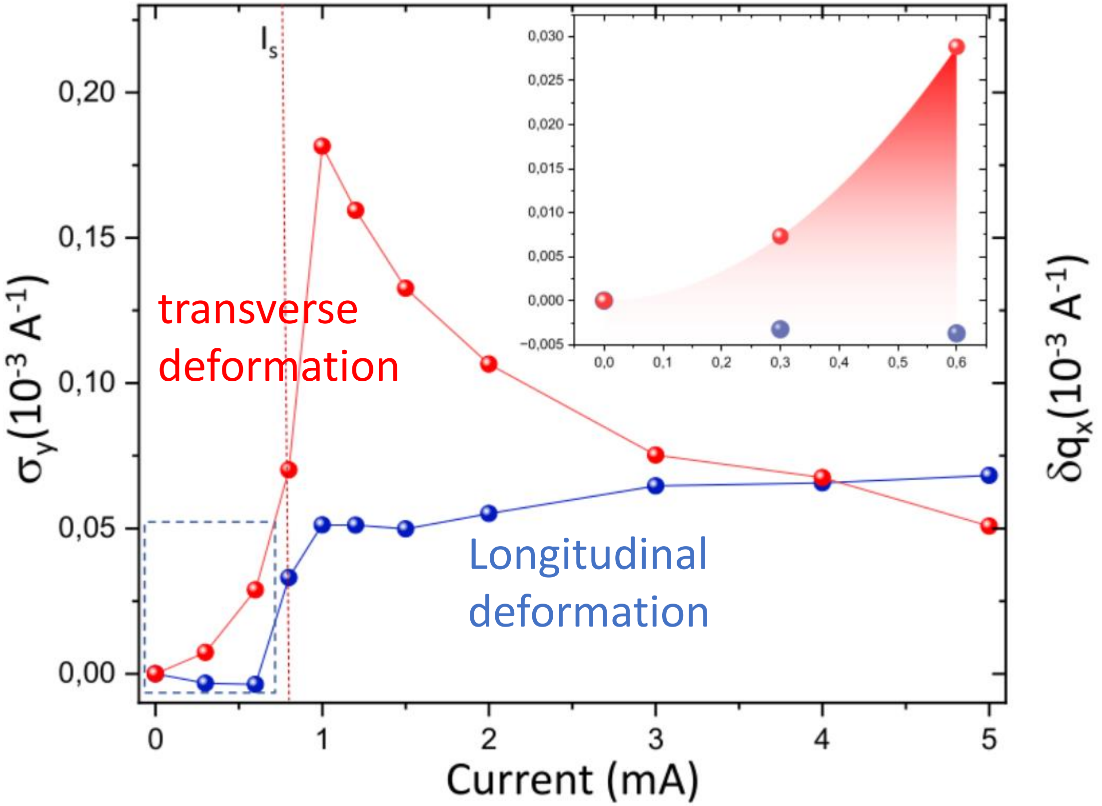
Sample image



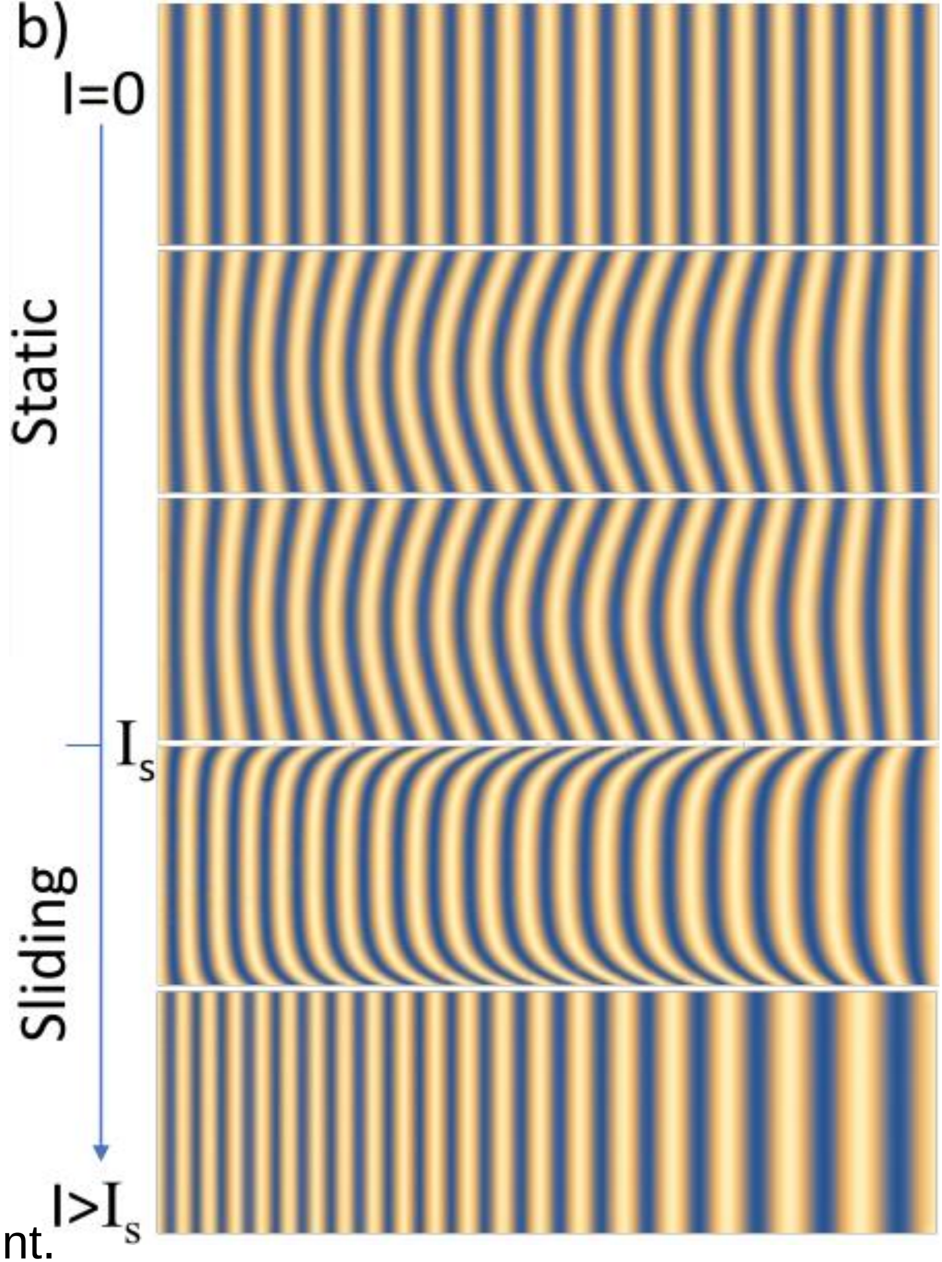


2D maps of the CDW state corresponding to 6 currents, below and above the threshold field (I_S=0.8mA) by using the CDW phase obtained from the fit. Wavefronts corresponding to a constant phase are represented in yellow. The two arrows show surface step position.

Transverse versus longitudinal deformations: closely linked



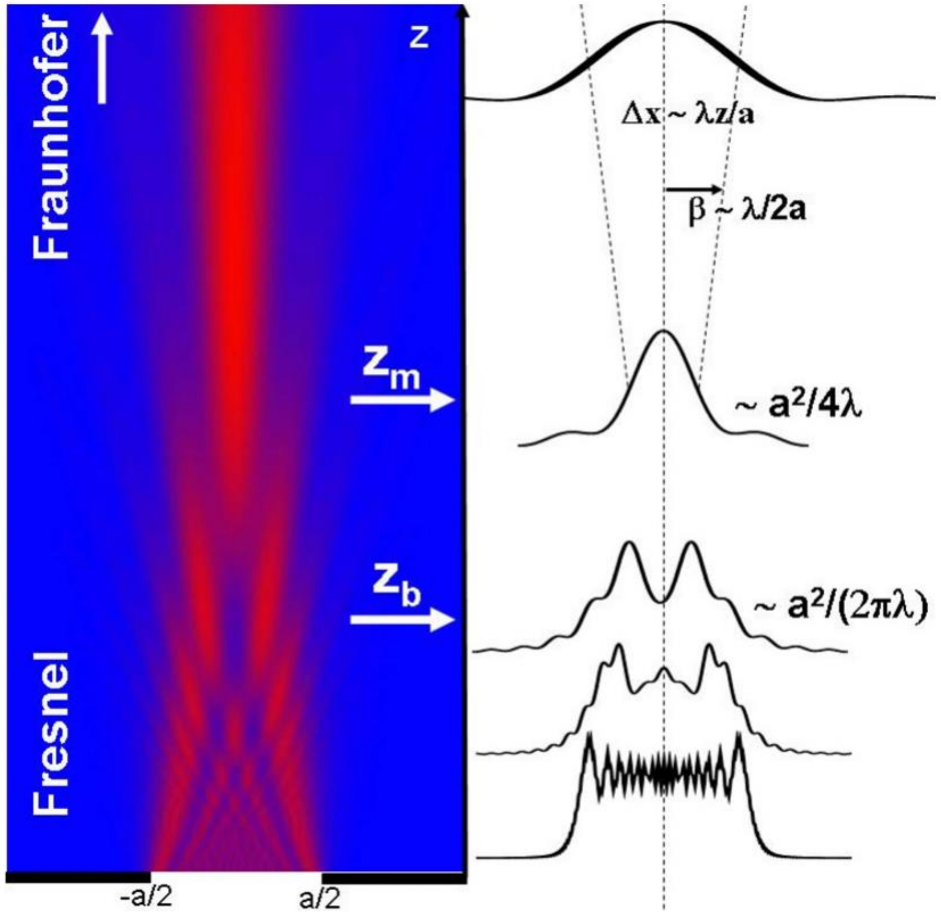
$$2\left(c_x^2\frac{\partial^2\phi}{\partial x^2}+c_y^2\frac{\partial^2\phi}{\partial y^2}+c_z^2\frac{\partial^2\phi}{\partial z^2}\right)-\omega_0^2\phi\approx\eta E$$



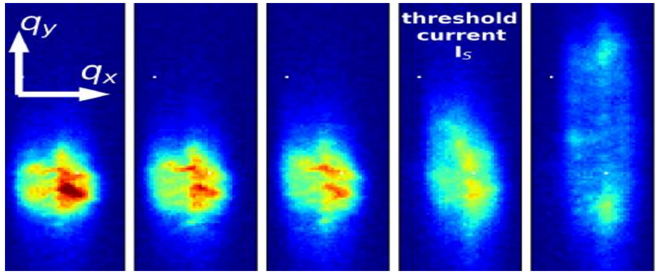
CDW deformation obtained by decreasing the ratio $c_y \lhd c_x$ with current.
Although this static model is phenomenological, it does reproduce the overall situation observed here, with an increasing compression and a decrease in curvature between two pinning centers above threshold.

Below threshold: Optical interpretation

$\alpha = \pi/2$

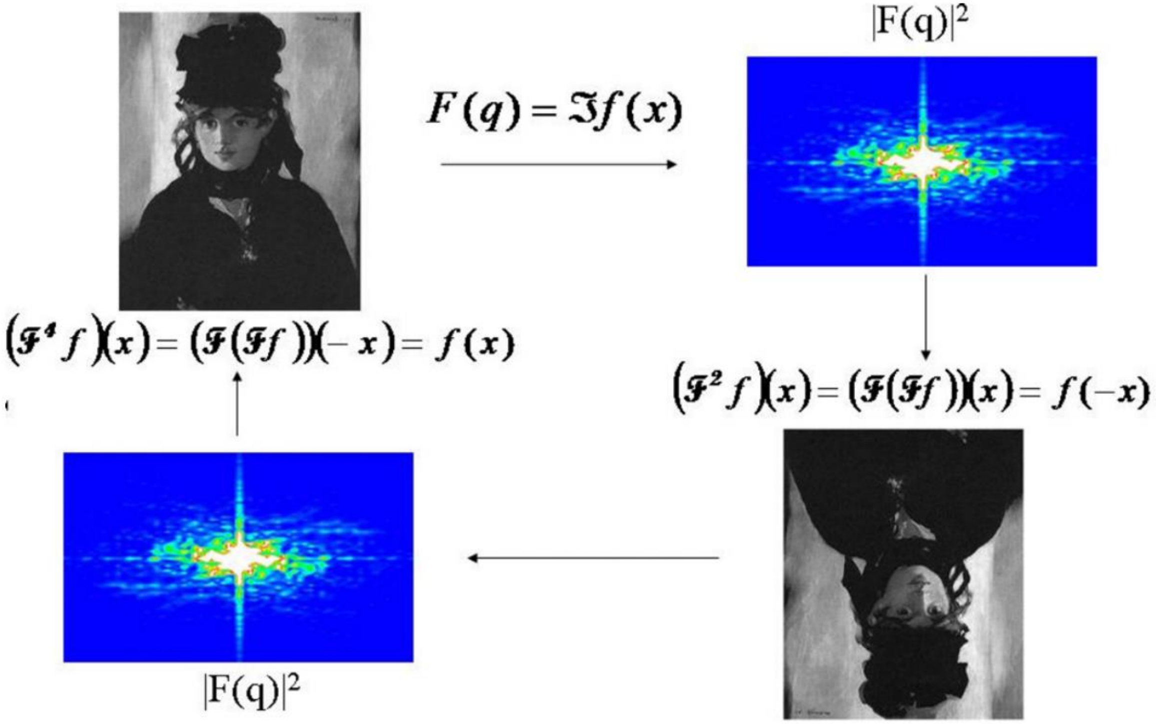


$\alpha = 0$



Manet (1872)
Berthe Morisot

The Fractional Fourier transform



Hard x-Rays
Dark point
position=1m
a=10µm
λ=1Å

$$\mathcal{F}_\alpha[g](q) = \int_{-\infty}^{\infty} K(q,x) g(x) du$$

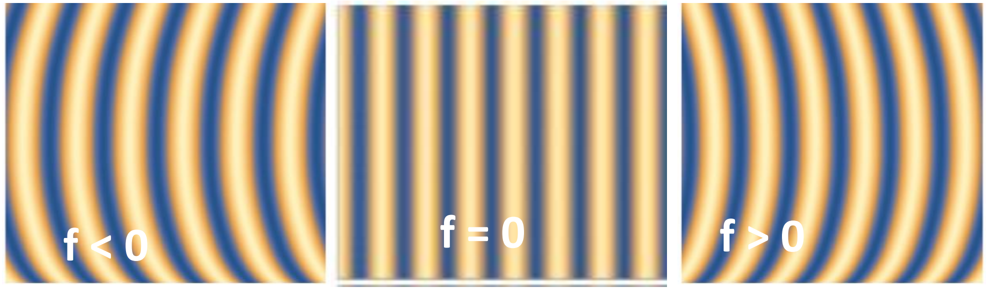
$$K(q,x) = \sqrt{\frac{1 - i\cot\alpha}{2\pi}} \exp[-i\frac{qx}{\sin\alpha} + \frac{i}{2}(q^2 + x^2)\cot\alpha]$$

FracFT: rotation de $\pi/2$
$\alpha=0$ identity
$\alpha = \pi/2$ Fourier Transform

V. Namias, J. Inst. Math. Appl. **25**, 241 (1980)
Le Bolloc'h, D and *Sadoc,* Eur. Phys. J. B, 81 (4): 481–487 (2009)

Diffraction of a bent CDW

$$\mathcal{F}_\alpha^f(q) \propto \int_{-a}^{a} \exp[-i\frac{qx}{\sin\alpha} + \frac{i}{2}(q^2+x^2)\cot\alpha]\exp[i2k_F x]\exp[if(x^2-a^2)]dx$$



$$\mathcal{F}_\alpha^f(q) = \mathcal{F}_{\alpha'}^0(q')$$

$$\cot\alpha' = \cot\alpha + 2f$$

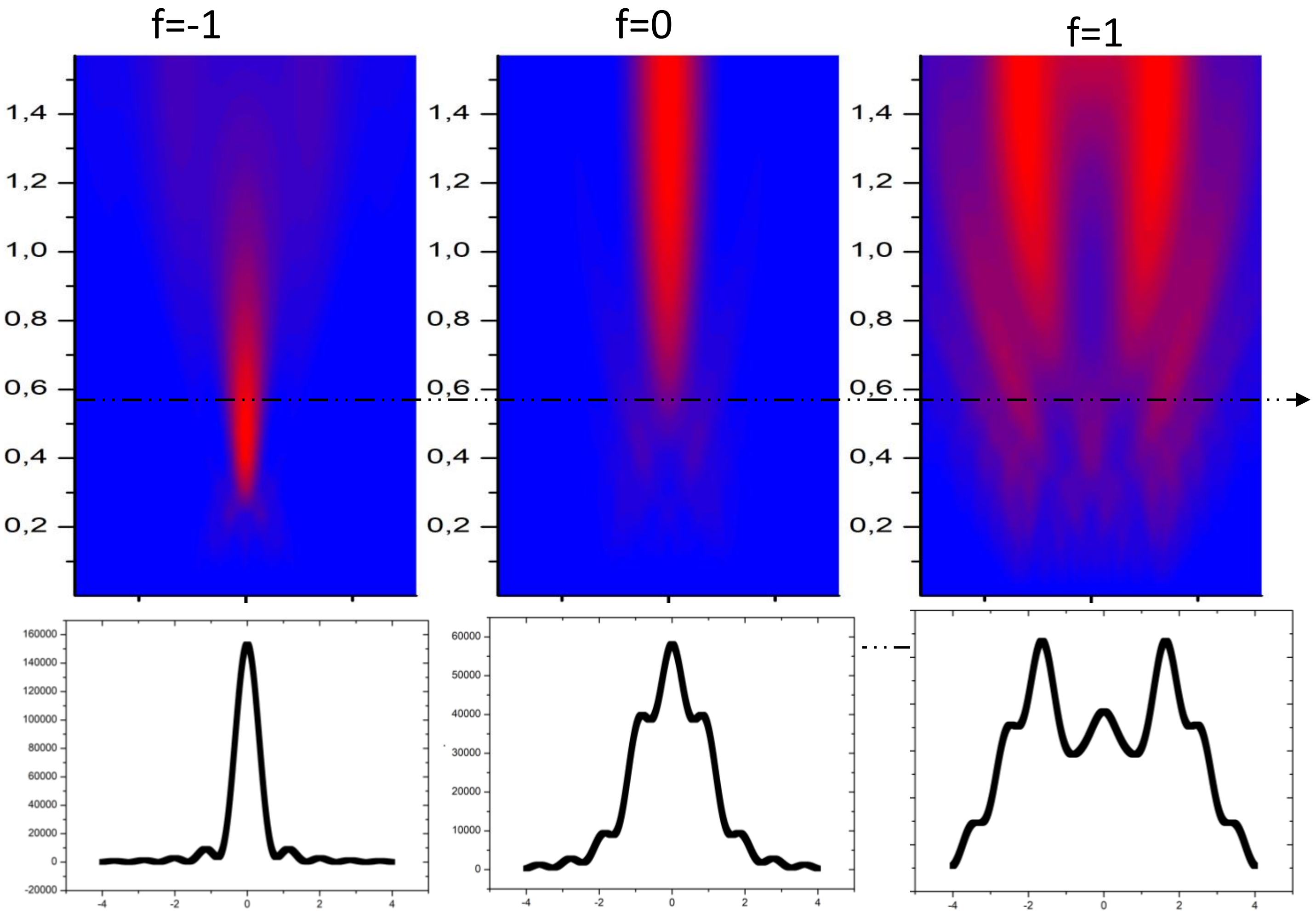
$$q'/q = \frac{1}{\sqrt{1+(\cot\alpha+2f)^2}}$$

Space curvature → Contraction/dilatation of space and time

A tunable electronic lens for hard X-rays ?

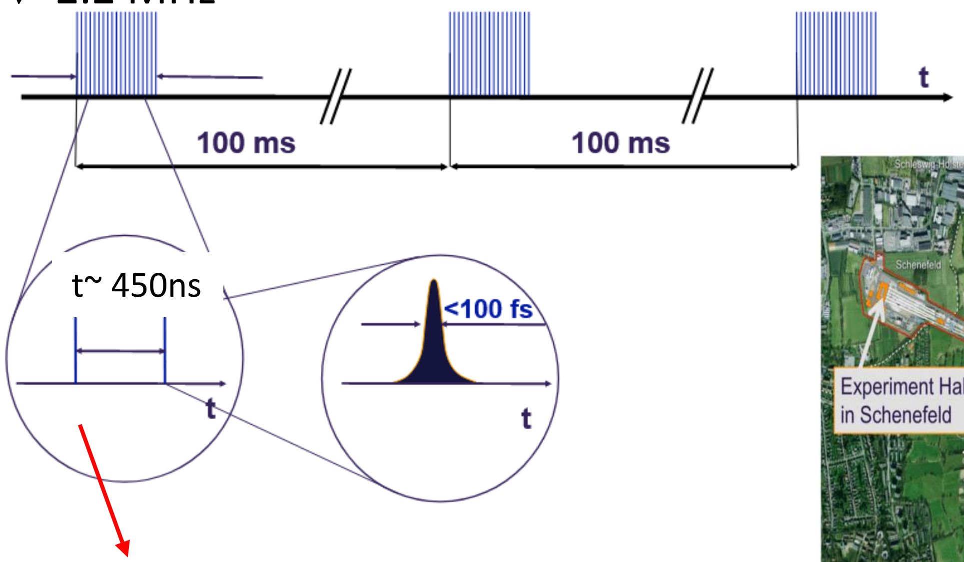
Not reflective lens (Kirkpatrick–Baez systems, capillaries, waveguides)
Not refractive (Be lenses)
and diffractive (Fresnel zone plate) optics.

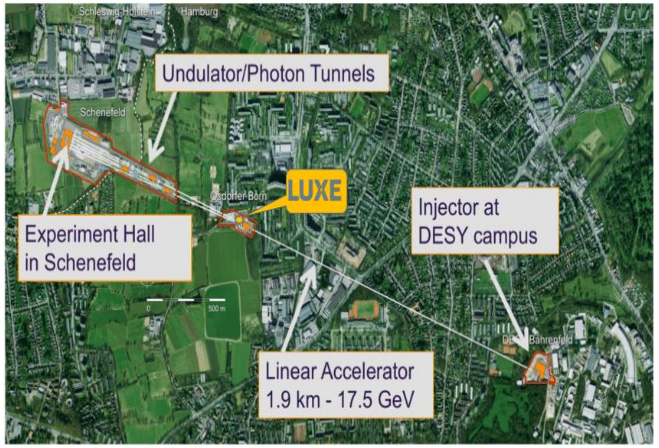
Continuous tunable lens, driven by a small applied electric field (either positve/negative; convergent/divergent lens
playing with Fresnel/Fraunhofer regime)
With restrictions
In 1D only/ Intensity ?

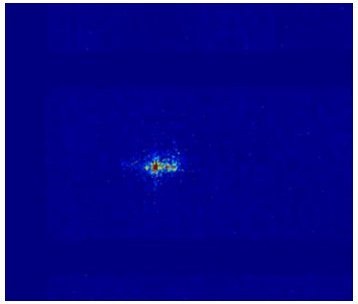


E-XFEL / MID beamline

Charge density wave submitted to an external dc current

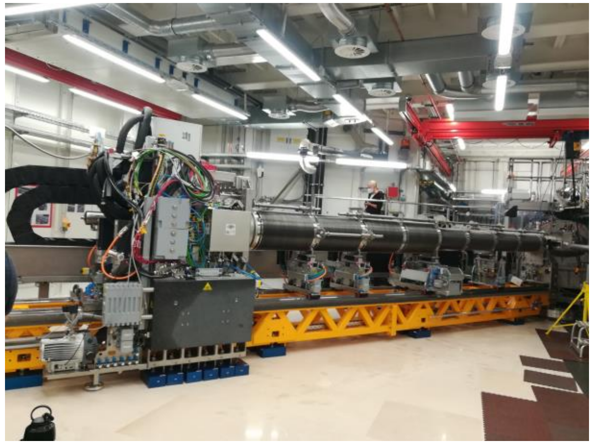






Stable from train to train, but ...

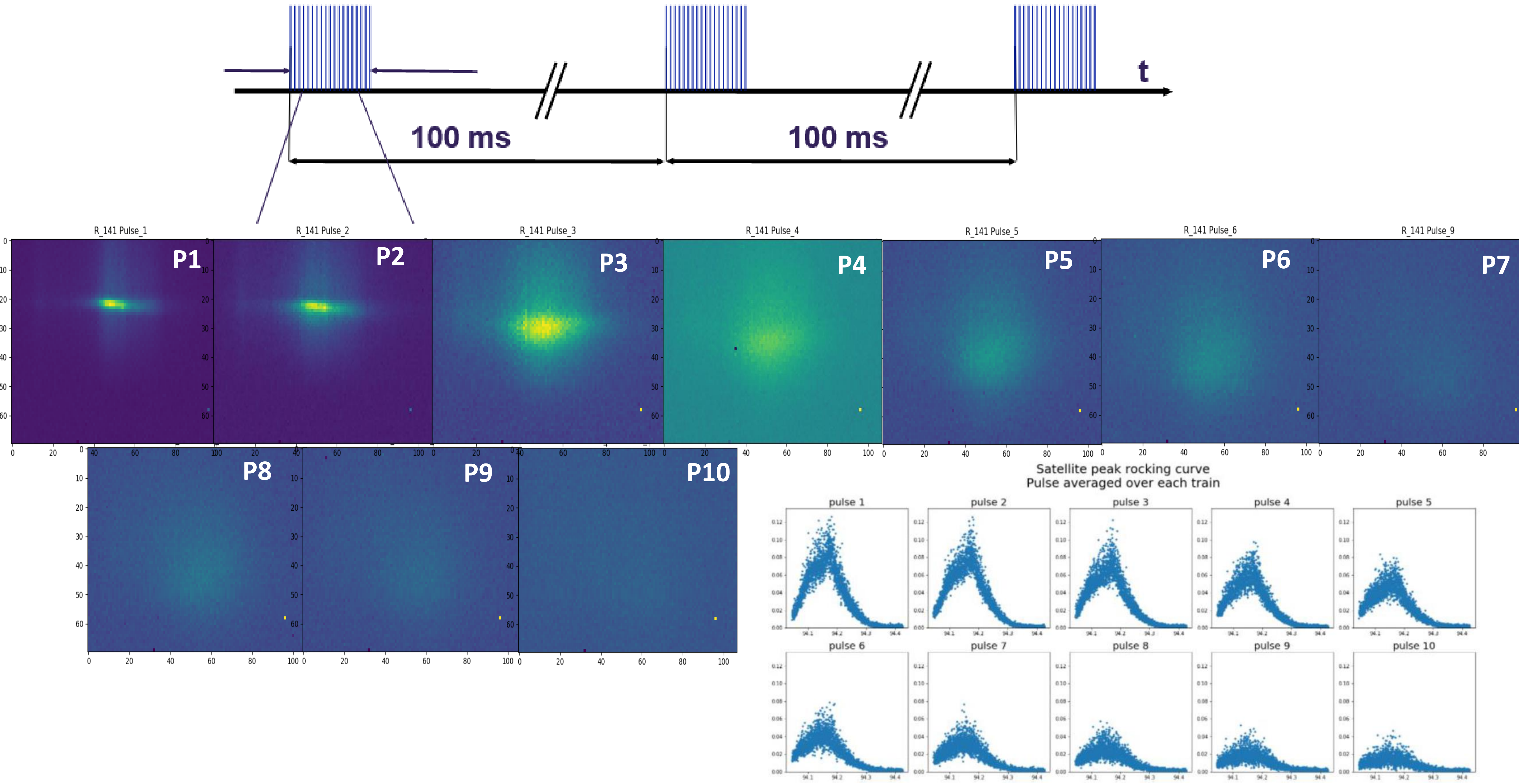
$Q(0\ 1.241\ 0)$ $NbSe_3$



- Beam properties :
  i. E=9keV
  ii. Seeding mode
  iii. Pink beam
  iv. pulse energy ~0.5 mJ = 3 10^{11} photons/pulse at 10 keV.

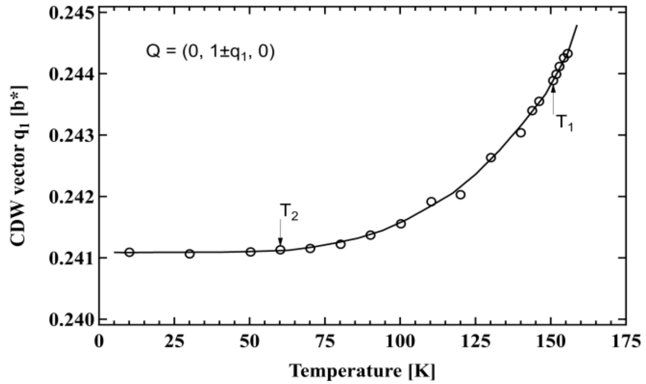
- Time Structure :
  i. pulse duration <100fs
  ii. 10 pulse trains/s (1 train each 100 ms = 0.1 s)
  iii. Each train is made of pulses (1~60 pulses/train)
  iv. Intra-bunch up to 2.2 MHz:
  i.e. Δt = 450 ns spacing between single pulses

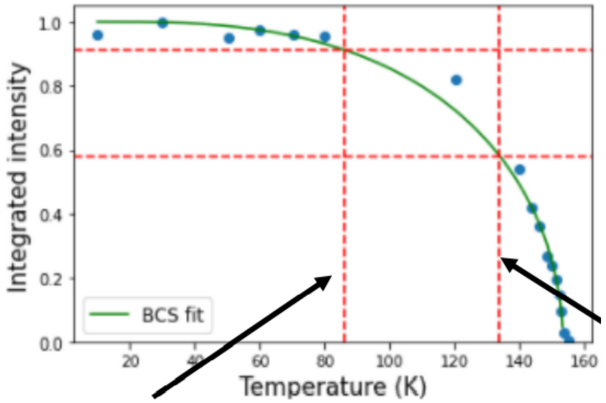
High resolution obtained from a single pulse



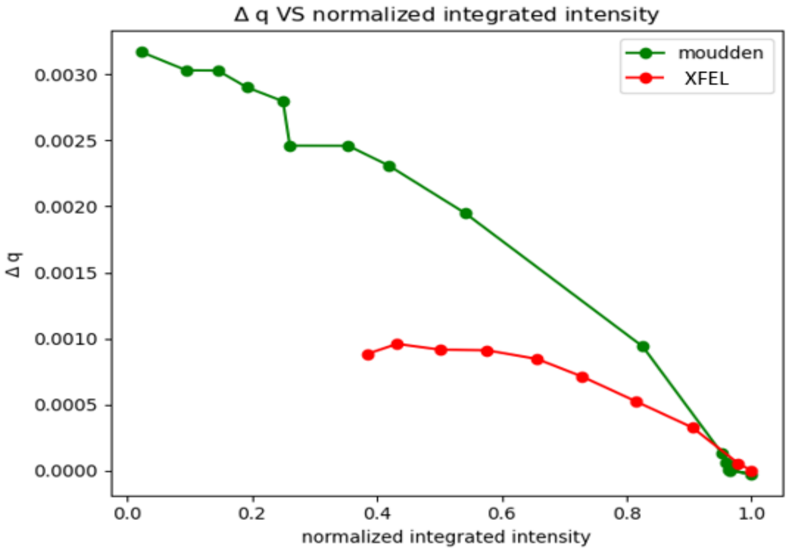
t
100 ms
100 ms
R_141 Pulse_1
R_141 Pulse_2
R_141 Pulse_3
R_141 Pulse_4
R_141 Pulse_5
R_141 Pulse_6
R_141 Pulse_9
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
Satellite peak rocking curve
Pulse averaged over each train
pulse 1
pulse 2
pulse 3
pulse 4
pulse 5
pulse 6
pulse 7
pulse 8
pulse 9
pulse 10

Heating effect ?



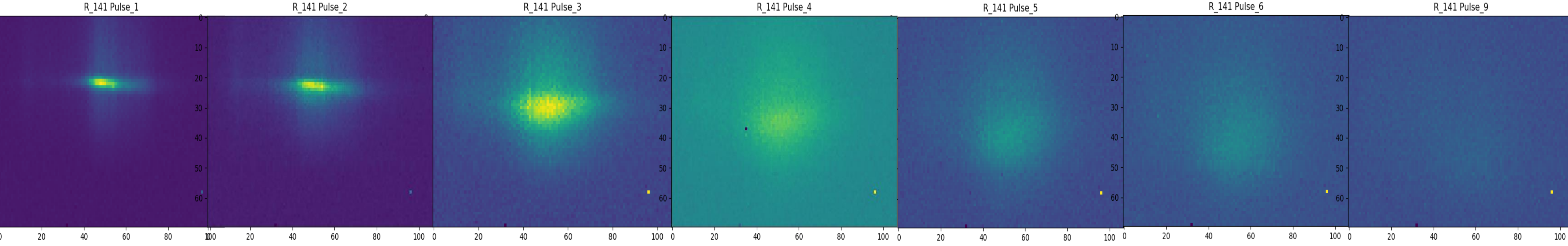


AH Moudden, JD Axe, P Monceau, F Levy, PRL 90



X-rays from XFEL sources pump and probe CDW systems
Out-of equilibrium

Same nature of the pump and probe
Split and delay ?



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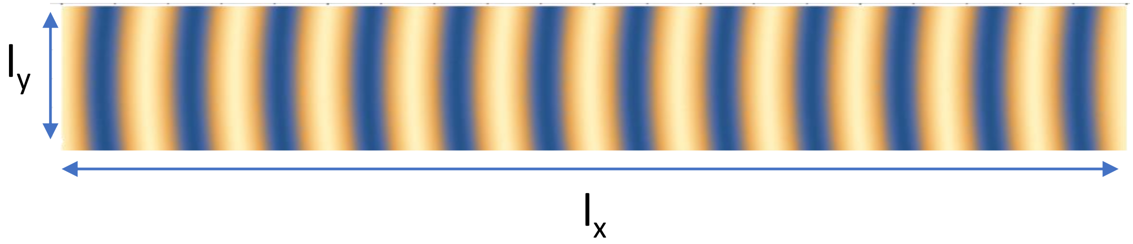
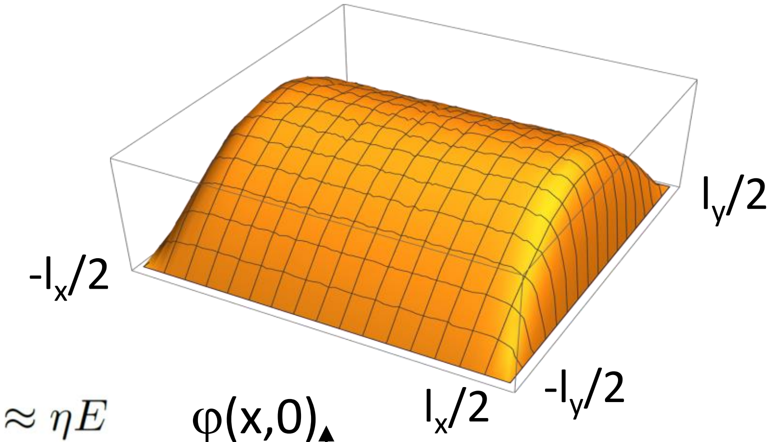
Thank you for your attention





$$2\left(c_x^2\frac{\partial^2\phi}{\partial x^2}+c_y^2\frac{\partial^2\phi}{\partial y^2}+c_z^2\frac{\partial^2\phi}{\partial z^2}\right)-\omega_0^2\phi\approx\eta E$$