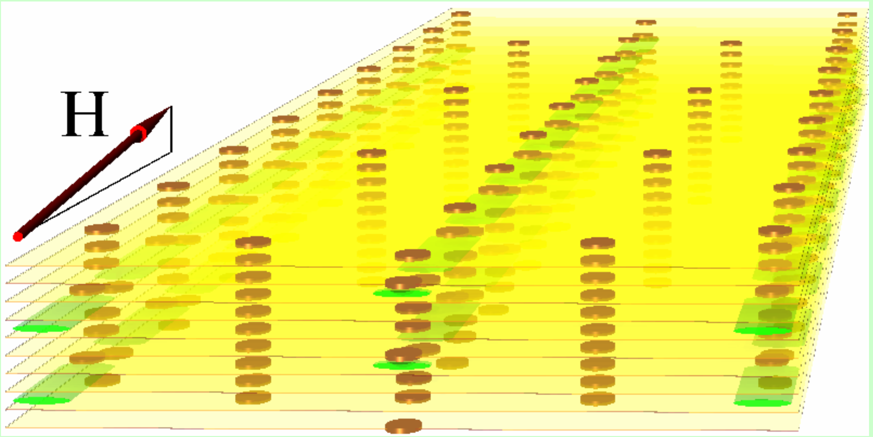
Vortex Lattices in Tilted Magnetic field



Collaborations:

C. Van der Beek, M. Konczykowski (Ecole Polytechnique, France)

Yu. Latyshev (IRE, Moscow)

V. Vlasko-Vlasov (MSD, ANL)

A. Grigorenko (Univ. of Manchester, UK) and S. Bending (Univ. of Bath, UK)

A. I. LARKIN MEMORIAL CONFERENCE

June 24-28, 2007, Chernogolovka, Russia

Argonne NATIONAL LABORATORY

PHYSICAL REVIEW B VOLUME 52, NUMBER 18 1 NOVEMBER 1995-II

Paramagnetic moment in field-cooled superconducting plates: Paramagnetic Meissner effect

A. E. Koshelev
Material Science Division, Argonne National Laboratory, Argonne, Illinois 60439
and Institute of Solid State Physics, Chernogolovka, Moscow District, 142432, Russia

A. I. Larkin
Material Science Division, Argonne National Laboratory, Argonne, Illinois 60439
and Landau Institute for Theoretical Physics, Moscow 117940, Russia
(Received 16 June 1995)

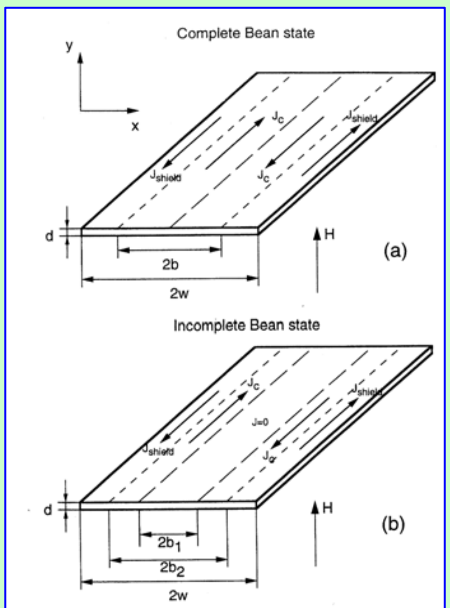
Motivation:

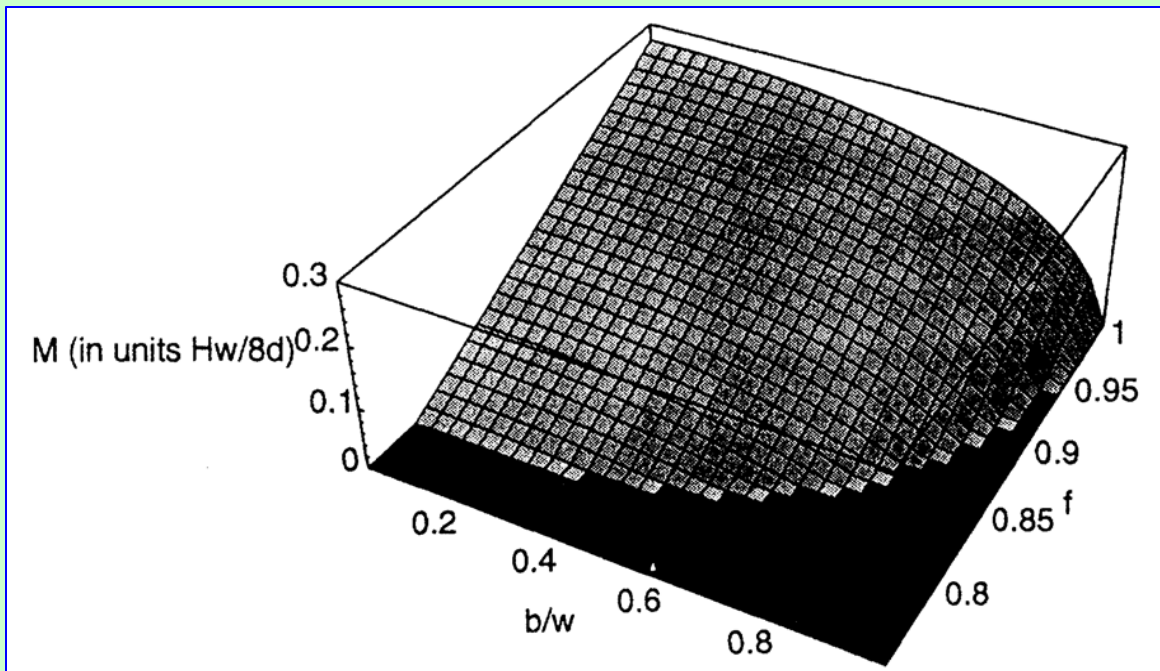
Paramagnetic Meissner effect in polycrystalline HTSC:

Spontaneous supercurrents due to random 0-π frustrations?

Problem: PME in Nb, P. Kostic *et al.*, Phys. Rev. B **53**, 791 (1996)

Alternative mechanism based on flux compression

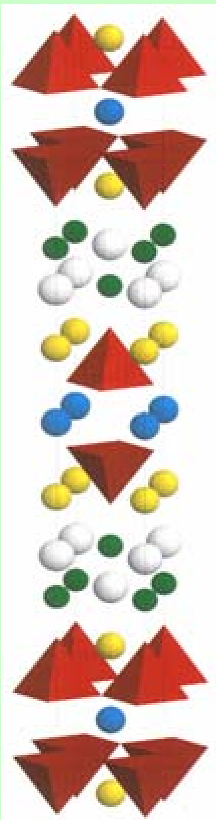




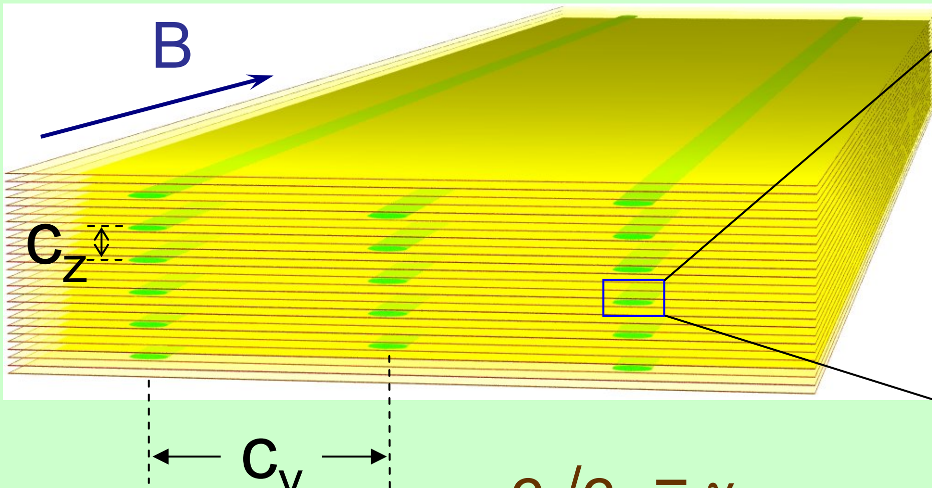
Lattice of Josephson vortices

$Bi_2Sr_2CaCu_2O_{8+\delta}$

(BSCCO)

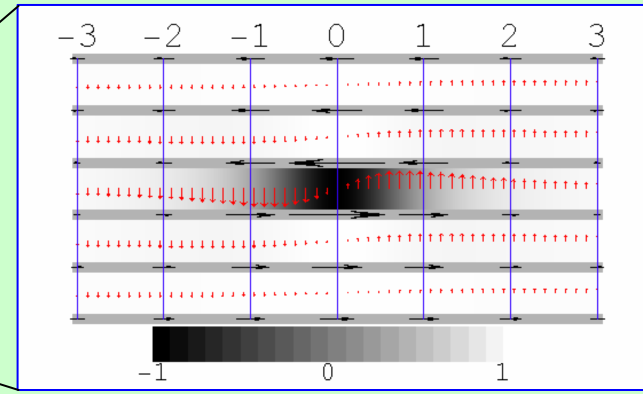


Small fields: Dilute lattice



$c_y/c_z = \gamma$

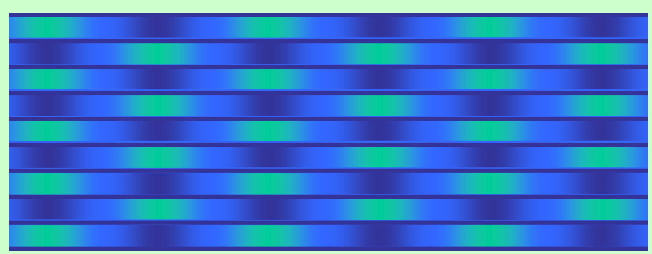
Core size $\lambda_J = \gamma s$



Bulaevskii 1973, Clem & Coffey 1991, AEK 1993

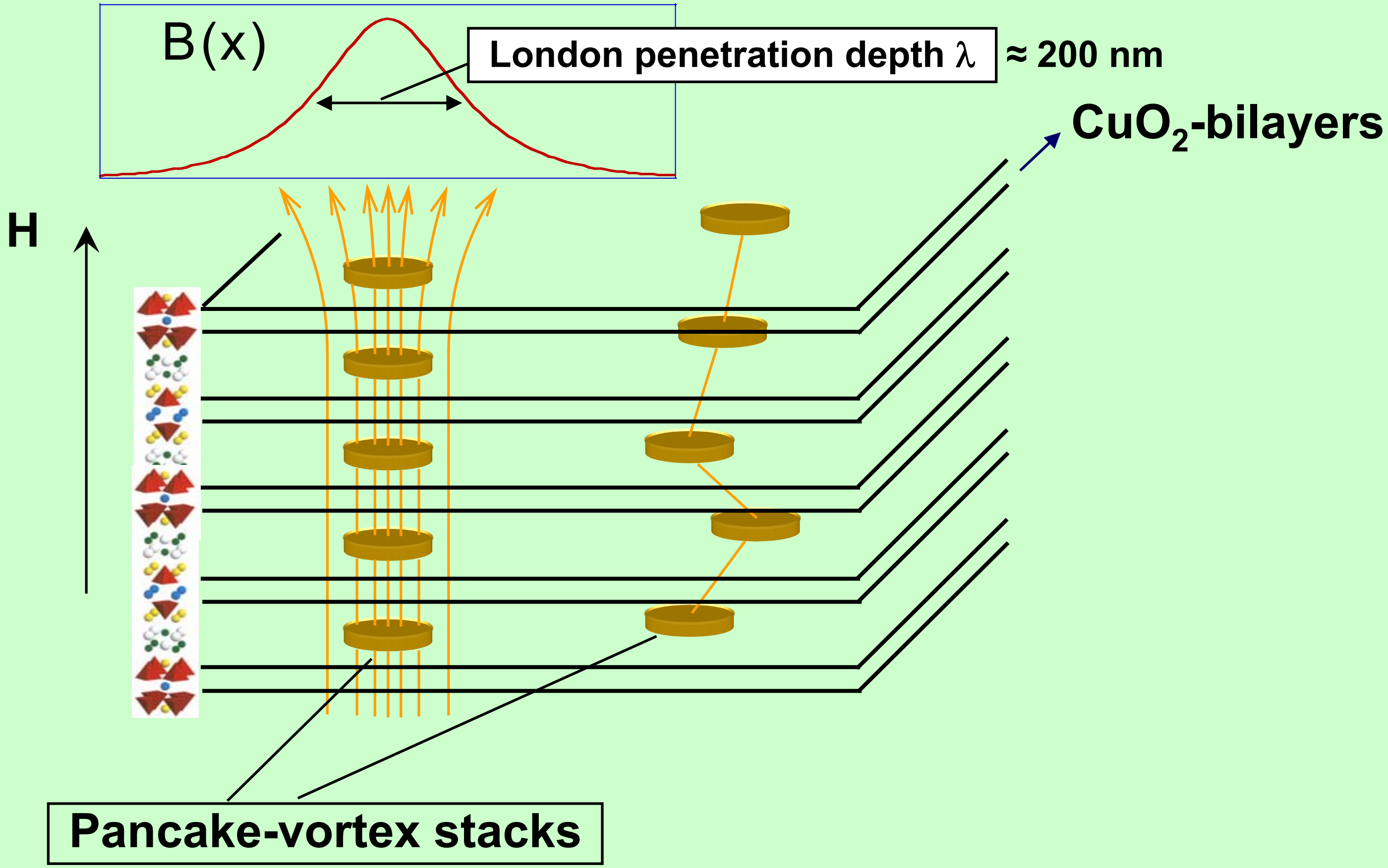
High fields $B_x > B_{cr} = \Phi_0/2\pi s\lambda_J$ (~ 0.5 T) : Dense lattice

Bulaevskii & Clem, 1991



Pancake stacks

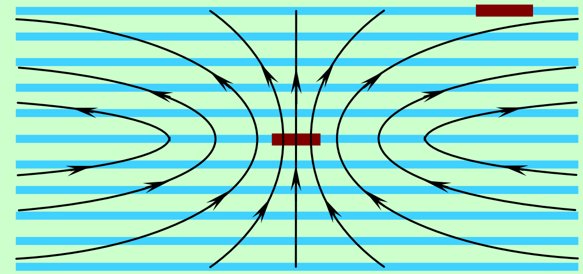
Efetov 1979, Artemenko&Kruglov 1990, Buzdin&Feinberg 1990, Clem 1991



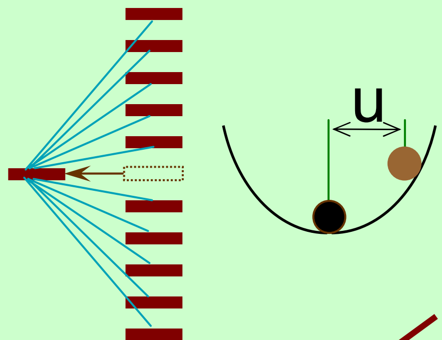
Magnetic and Josephson coupling

Magnetic coupling:

- nonlocal: range λ
- weaker than in-plane interaction by s/λ

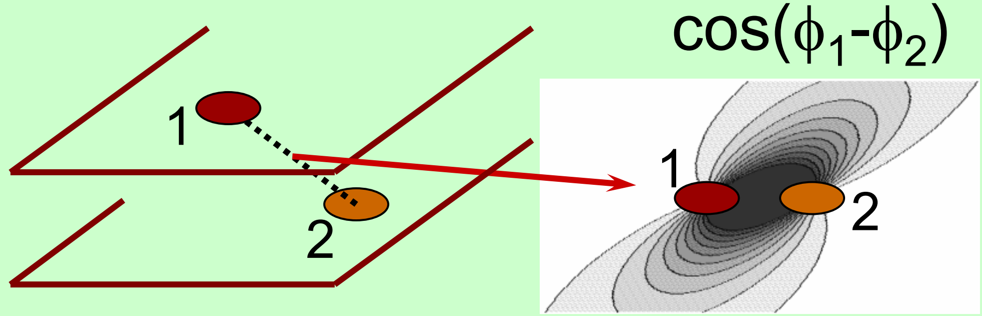


Magnetic cage:



Josephson coupling:
phase mismatch between neighboring layers

$\cos(\phi_1 - \phi_2)$



$- E_J \cos(\phi_1 - \phi_2)$

Relative strength: Parameter $\alpha = \lambda/\gamma s$

BSCCO: $\gamma = 200 - 700$

$\lambda/s = 130 – 250$

$\alpha = 0.3\text{-}0.9$

Argonne NATIONAL LABORATORY

Interaction between Jos. vortex and pancake stacks

Crossing configuration

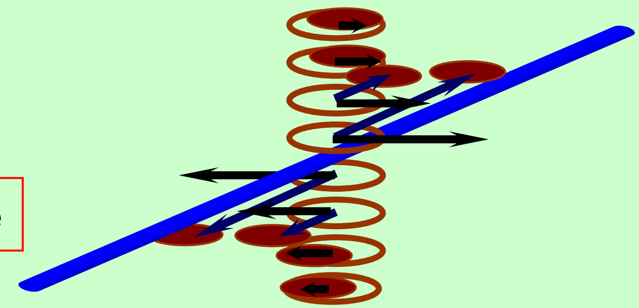
Phys.Rev.Lett. **83,** 187 (1999)

Deformation energy

$$E = \sum_n \left(-\frac{s\Phi_0}{c} j_n(0)\, u_n + \frac{K u_n^2}{2} \right)$$

Jos. Vortex current

Magnetic cage



Crossing energy

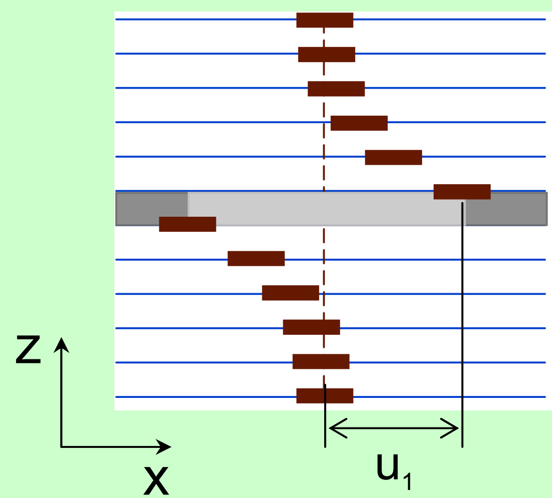
$$E_\times = -\frac{\Phi_0^2}{2\pi^2\gamma^2 s \ln(3.5\gamma s/\lambda)}$$

~ 200 K

Maximum displacement:

$u_1 = \lambda^2/\gamma s$ ~ 100 nm

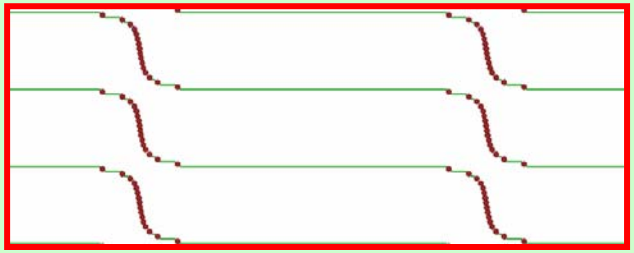
Numerics: instability at $\alpha = \lambda/\gamma s \approx 0.69$



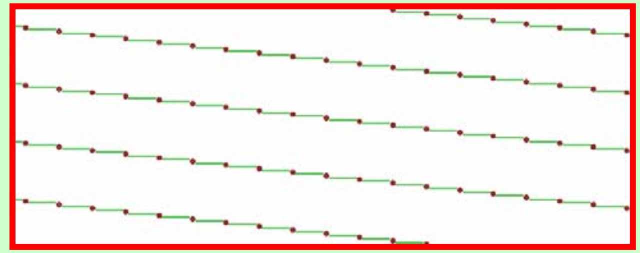
Argonne NATIONAL LABORATORY

Penetration of c-axis field in presence of in-plane field

stacks vs kinks



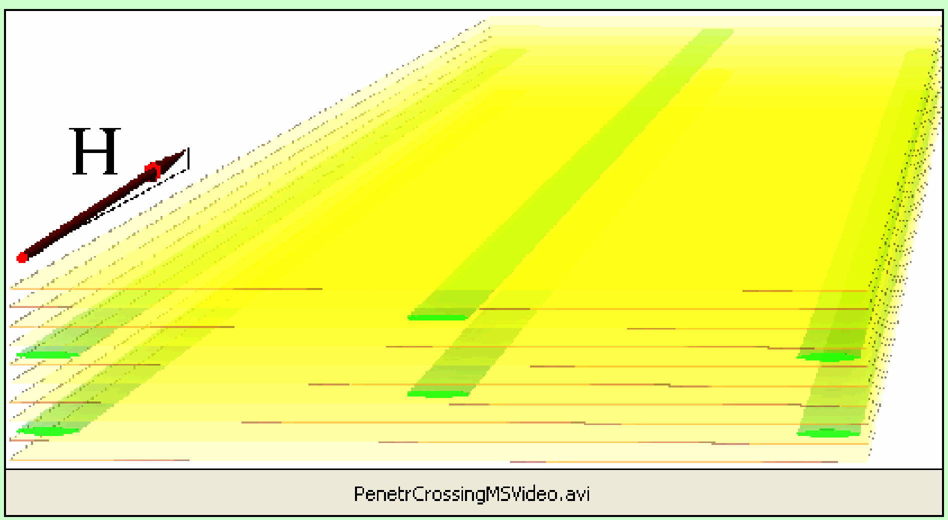
Bulaevskii *et al.* 1992; Huse 1992; AEK, 1999…



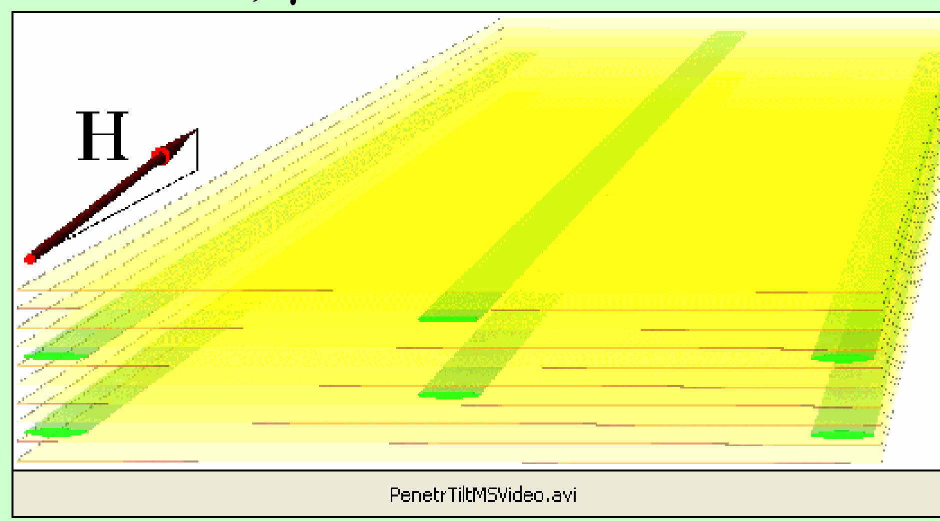
Feinberg *et al.* 1990; Ivlev *et al.* 1991; Bulaevskii *et al.* 1992 …

$\alpha = \lambda/\gamma s = 0.45\text{-}0.5$

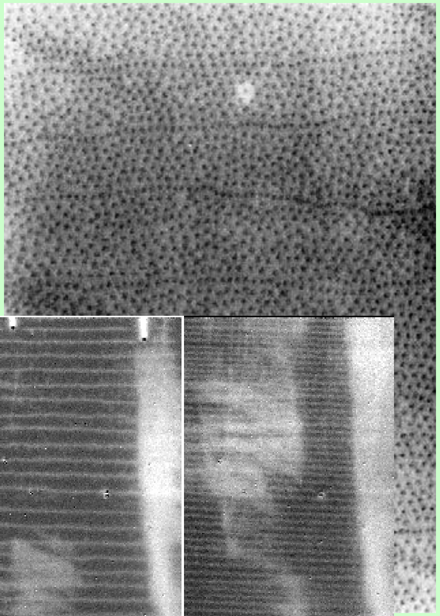
$\alpha < 0.3$



$\alpha > 0.7, \gamma \gg 1$



Visualization

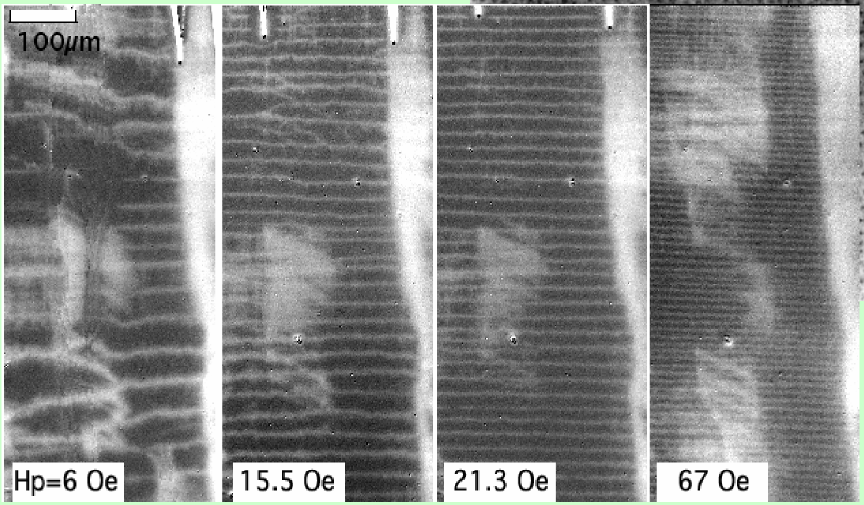


Decorations:

Bolle *et al.*, PRL, 1991
Grigorieva *et al.*, PRB, 1995
Tokunaga *et al., PR B, 2003*
(Tamegai Group)

Magnetooptics:

Vlasko-Vlasov *et al.*, PR B 2002
Tokunaga *et al.*, PR B, 2002



Also:

Lorentz microscopy:

Matsuda *et. al*.(Tonomura group), *Science, 2001*

Scanning Hall Probe:

Grigorenko *et. al.* (Bending group), Nature, 2001

Argonne NATIONAL LABORATORY

Outline

- Vortex-chain states and transitions
- Josephson vortex inside pancake-vortex lattice
- Phase diagram in tilted fields at intermediate anisotropies

Argonne NATIONAL LABORATORY

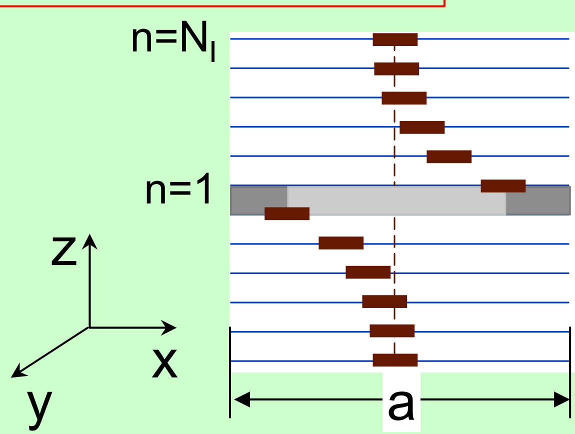
Lawrence-Doniach model in London limit

Regular phase $\phi_n(x,y)$ + pancake displacements u_n (vortex phase $\phi_{v,n}$)

Energy (distances, $x,y < \lambda_c$, $z < \lambda_{ab} \rightarrow$ no screening):

$$E[\phi_n, u_n] = \sum_n \int d^2r \left[\frac{J}{2}(\nabla\phi_n)^2 + E_J\left(1 - \cos\left(\phi_{n+1} - \phi_n + \phi_{v,n+1} - \phi_{v,n} - \frac{2\pi s}{\Phi_0} B_x y\right)\right)\right]$$
$$+ \frac{1}{2}\sum_{n,m} U(u_n - u_m)$$

Full 3D model was used to study isolated chain



2D model (pancake vortex lattice, at $a < \gamma s$):

1. $\phi_n(x,y) = \bar{\phi}_n(y) + \tilde{\phi}_n(x,y)$
2. $\tilde{\phi}_n(x,y) \approx \tilde{\phi}_{v,n}(x,y)$
3. $F_{J,loc}\left[\bar{\phi}_n, u_n\right] = E_J \int dxdy \left[\cos(\tilde{\phi}_{n+1} - \tilde{\phi}_n + \bar{\phi}_{n+1} - \bar{\phi}_n) - \cos(\bar{\phi}_{n+1} - \bar{\phi}_n)\right]$

Local Josephson energy

Argonne NATIONAL LABORATORY

Vortex Chains in tilted fields

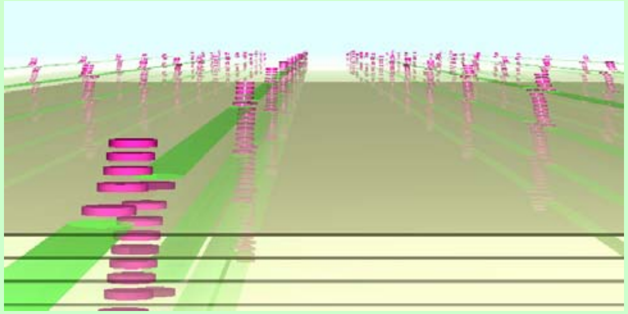
Phys. Rev. B **71**, 174507 (2005)

Dilute Josephson vortex lattice + very small c-axis field → Vortex Chains

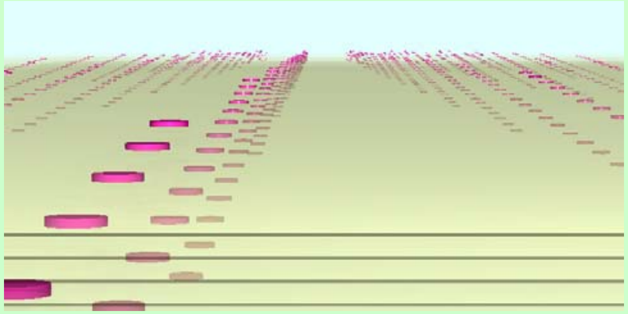
key parameter $\alpha=\lambda/\gamma s$

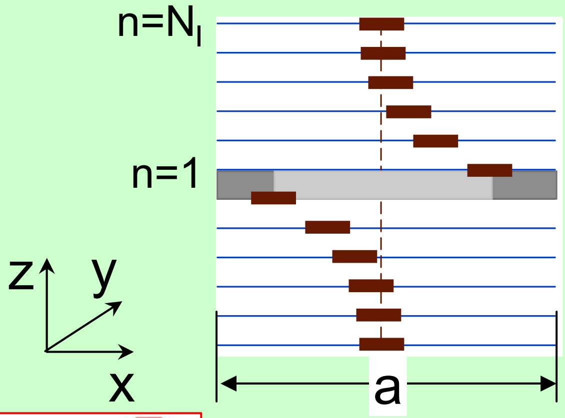
Really high anisotropy $\alpha < 0.3$ vs not-so-high anisotropy $\alpha > 0.7$

Crossing Chains



Tilted Chains





Competition between

Magnetic coupling and interaction with JVs

(likes straight stacks) (likes tilted stacks)

two periods: a and $N = 2N_l$

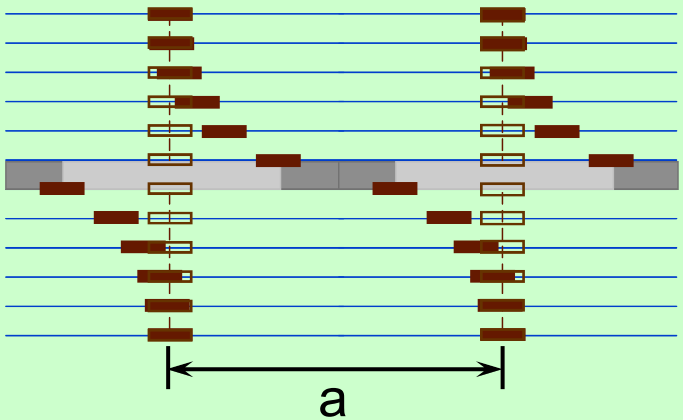
Attraction between deformed stacks

A. Buzdin and I. Baladié, PRL 2002

Interaction energy for a < γs

$$U_{int}(a) = 2\varepsilon_0 \left[K_0(a/\lambda) - \frac{\langle u^2 \rangle}{a^2} \right]$$

$$K_0(a/\lambda) \propto \exp(-a/\lambda)$$

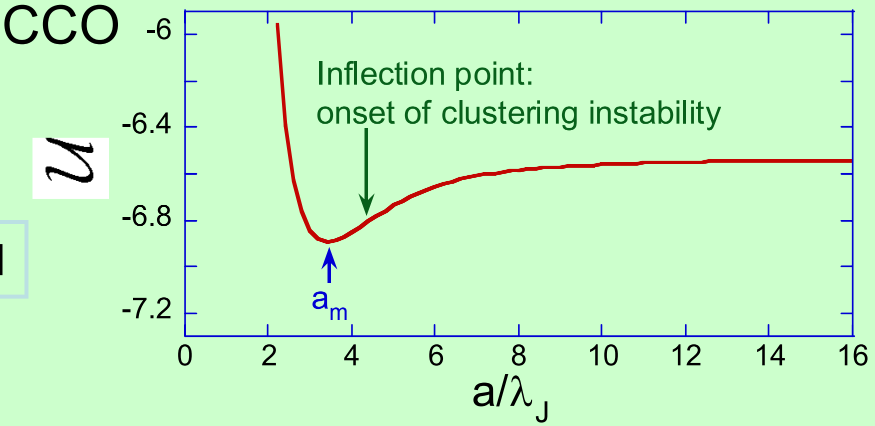


Minimum of $U_{int}(a)$ at $a_m = \lambda \ln \frac{C\lambda^2}{\langle u^2 \rangle}$

Chains with $a > a_m$ do not realize

Valid only if $a_m < \gamma s \rightarrow$ not practical for BSCCO

In general: $\min_a [\mathcal{U}(a)]$ → Energy per unit cell

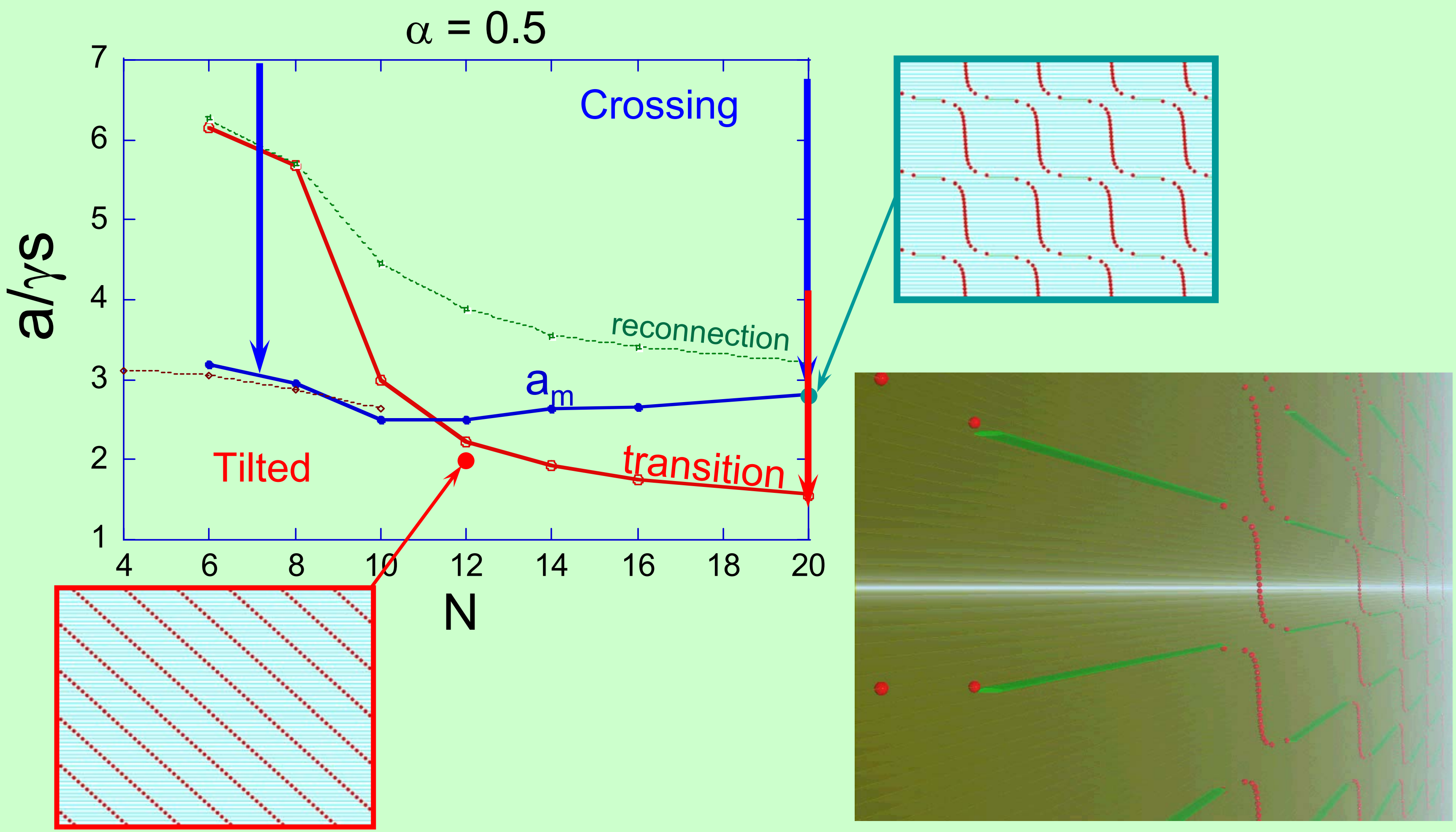


Also: attraction between tilted stacks

Buzdin and Simonov, JETP Lett. (1990); Grishin, Martynovich, and Yampolskii, JETP (1990).

1st scenario, $0.4 < \alpha < 0.55$

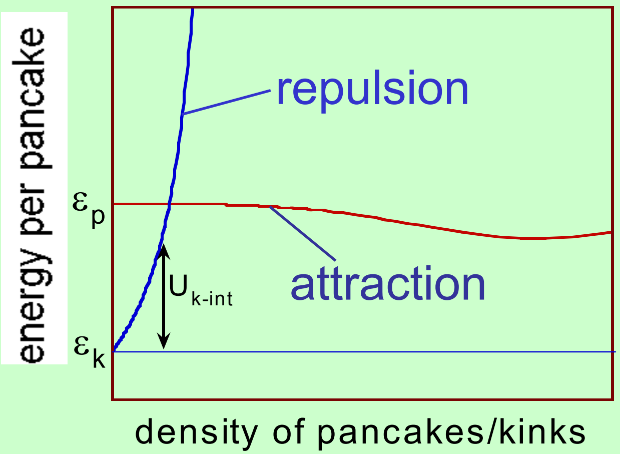
Locked → Crossing Chain → Tilted Chain

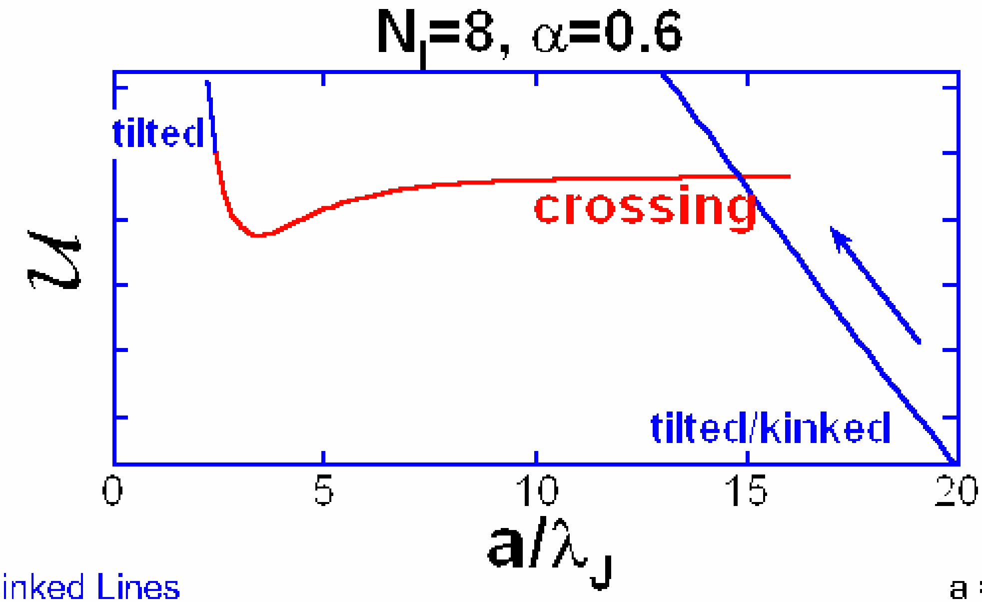


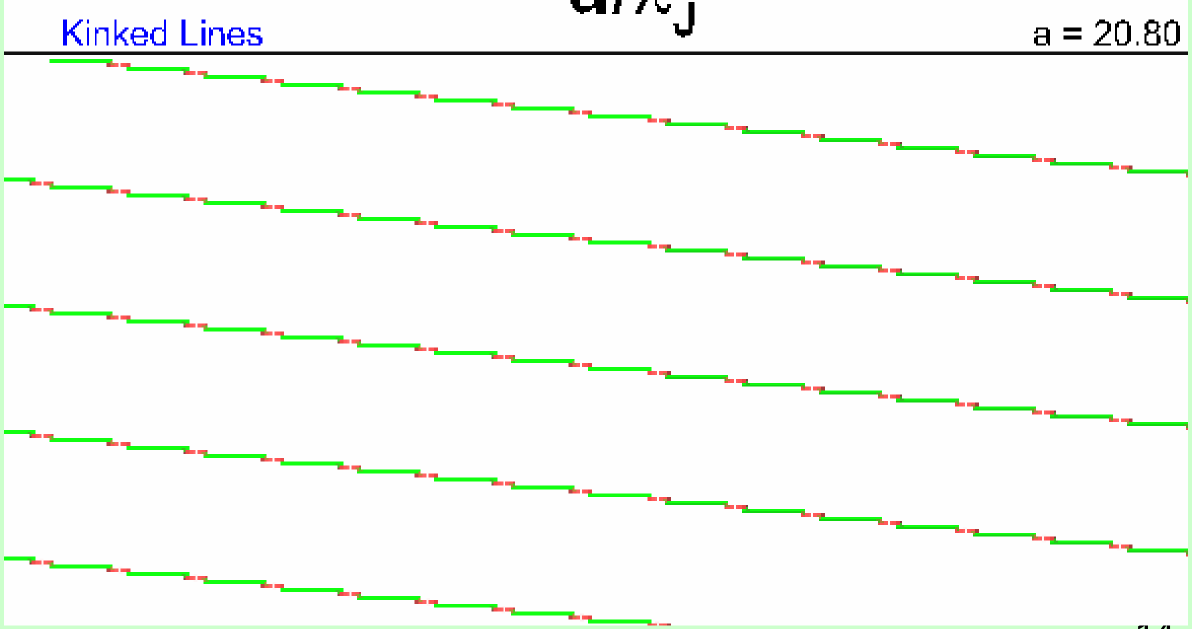
2^{nd} scenario $0.55 < \alpha < 0.65$

Locked → Kinked → Crossing Chain → Tilted Chain

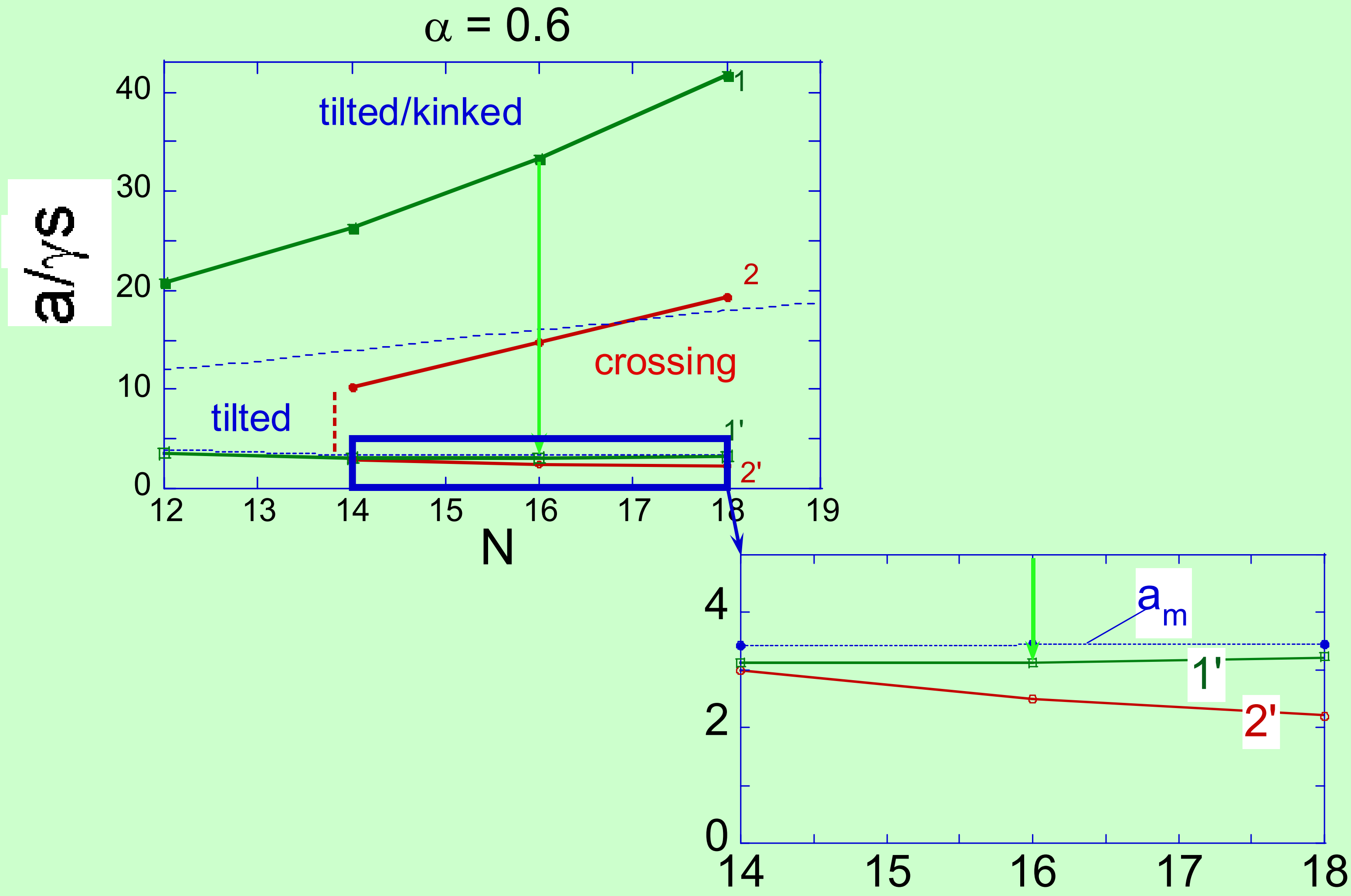
1. kink penetration
2. 1^{st} order transition due to competing interaction energies







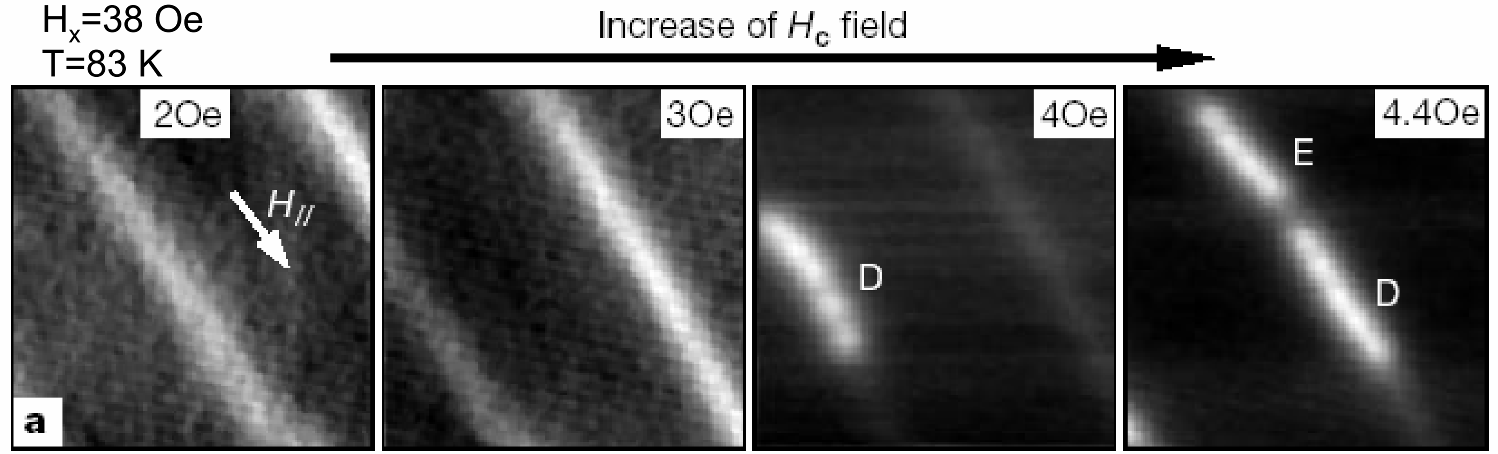
Typical phase diagram for $0.5 < \alpha < 0.65$



Experimental observation of transition

A. Grigorenko *et. al.* (S. Bending Group), *Nature, 2001*

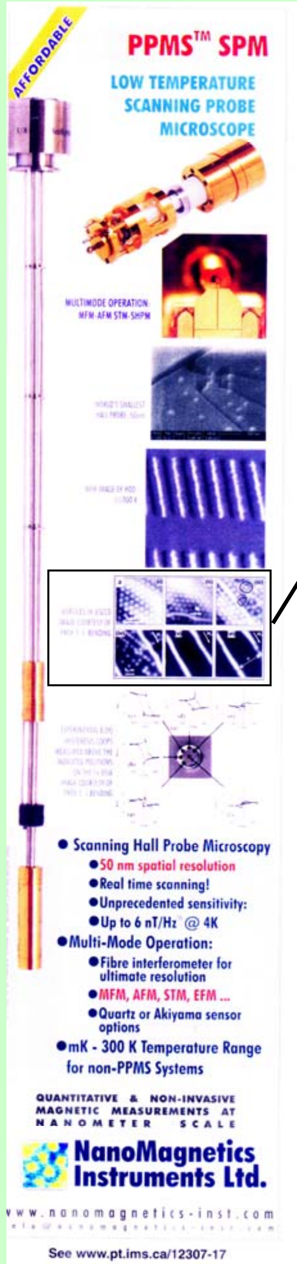
Transition to tilted chains
M. Dodgson, Phys. Rev. B 2002

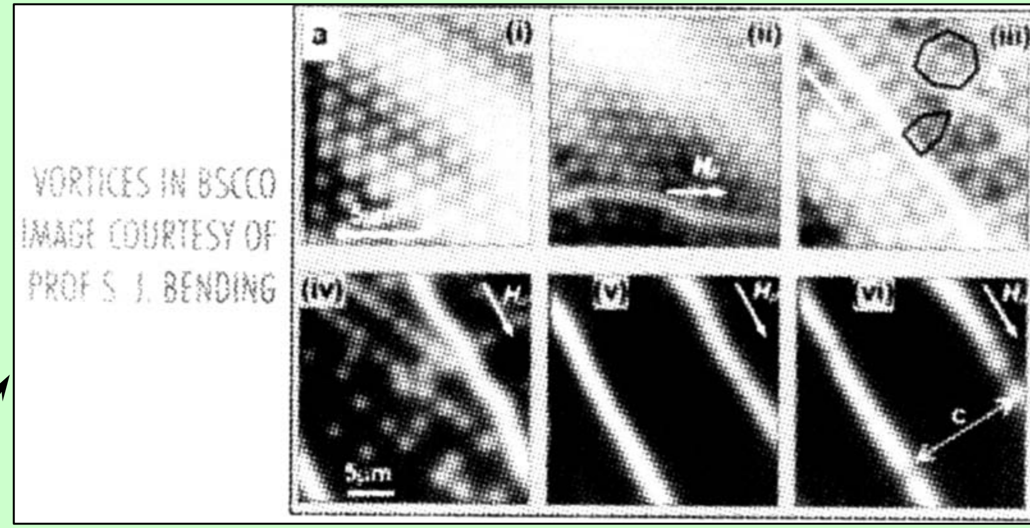


"… as H_c is increased further, `crystallites' of well resolved PV stacks, with ten times higher flux density, nucleate and grow (H_c = 4Oe and 4.4 Oe)."

Vortex Chains: practical application

Physics Today: Advertisement of Scanning Probe Microscope





In-plane vortex inside dense pancake lattice

B_z = 10 – 100 G

Crossover Josephson vortex → soliton

Physical Review B **68**, 094520 (2003)

Argonne NATIONAL LABORATORY

Renormalization of Josephson vortex by pancakes

$\alpha = \lambda/\gamma s \ll 1$

$\alpha = 0.2$

Typical field

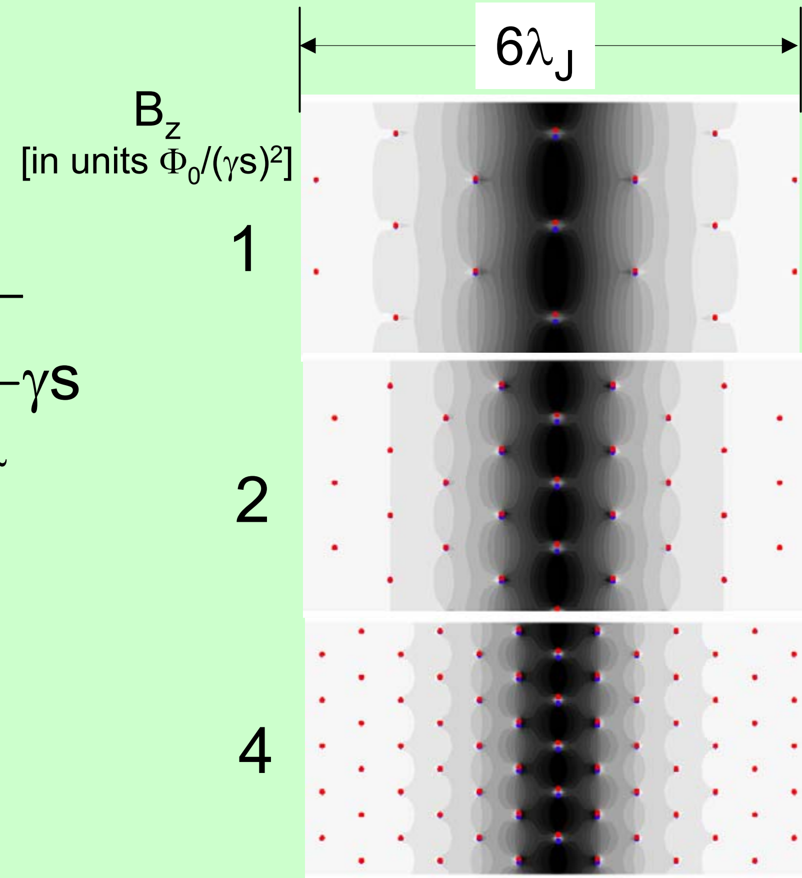
$$B_\lambda = \frac{\Phi_0}{4\pi\lambda^2}\ln\frac{a}{r_w} \quad \sim 30\text{ -}70\text{ G}$$

Vortex energy

$$\varepsilon_J = \sqrt{\frac{B_\lambda}{B_z + B_\lambda}}\varepsilon_{J0}$$

Core size

$$\lambda_J = \sqrt{\frac{B_\lambda}{B_z + B_\lambda}}\gamma s$$



Dense Lattice, $B_z > B_\lambda$:

Maximum displacement $u_1/a \approx 0.5\,\alpha$

Number of rows in the core $\approx 1/\alpha$

Argonne NATIONAL LABORATORY

Solitonlike cores at $\alpha > 0.5$

$$B = \Phi_0/(\gamma s)^2$$

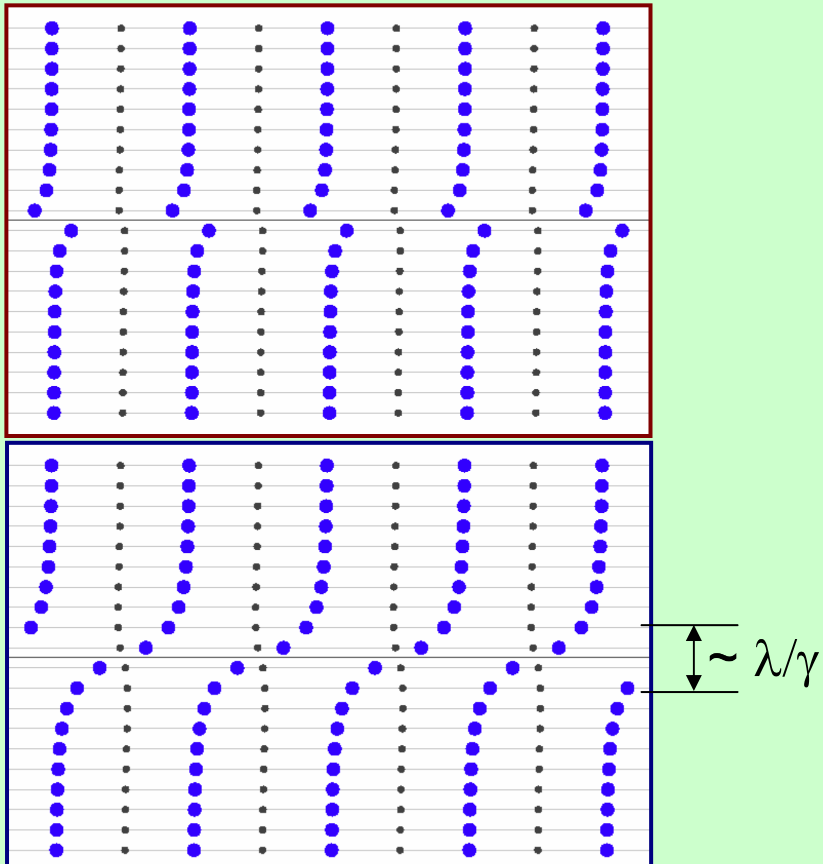
Displacements
in the central row

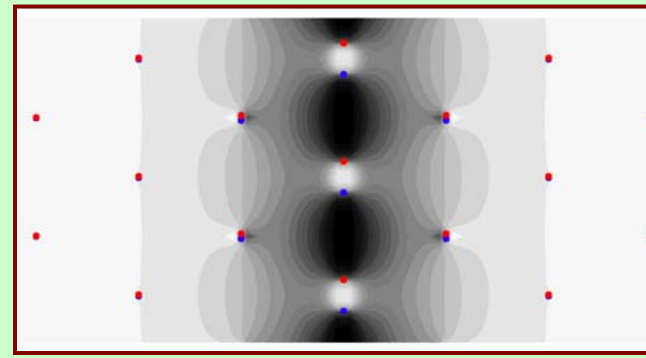
Phase difference
between two central layers

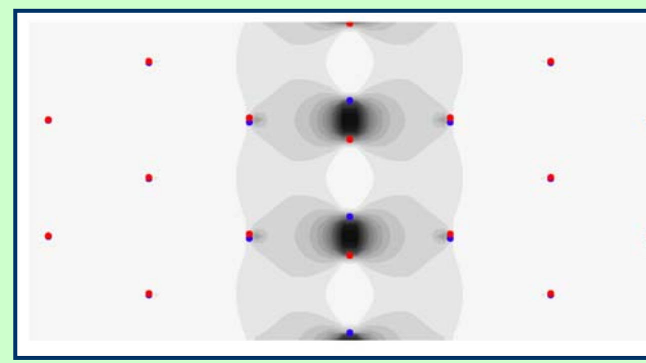
$\lambda/\gamma s$

0.3

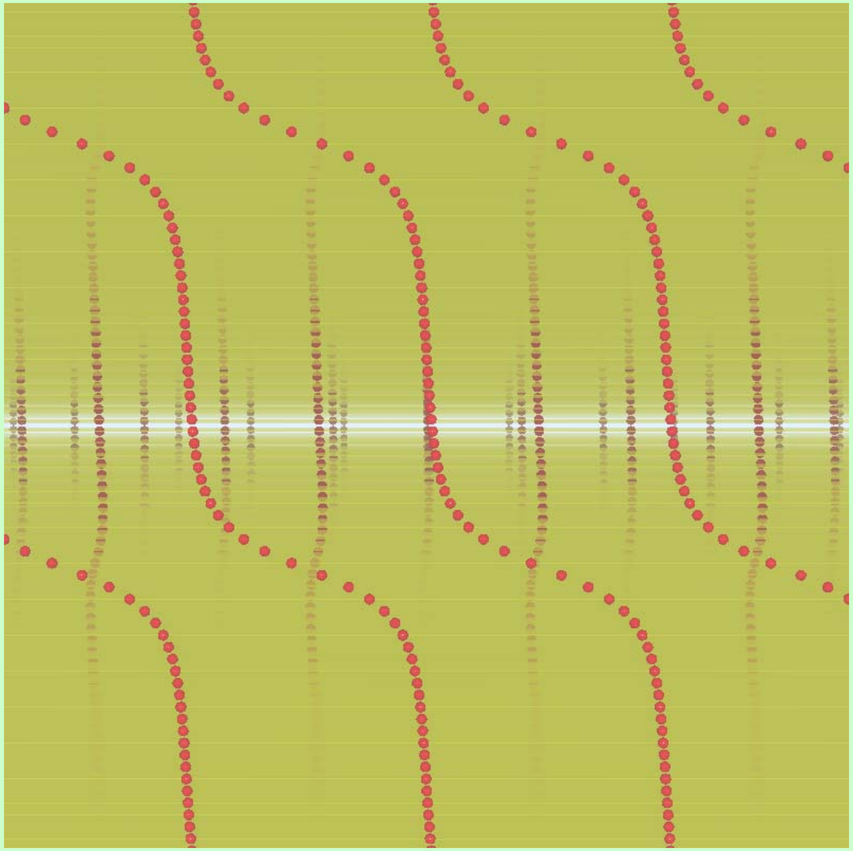
0.5

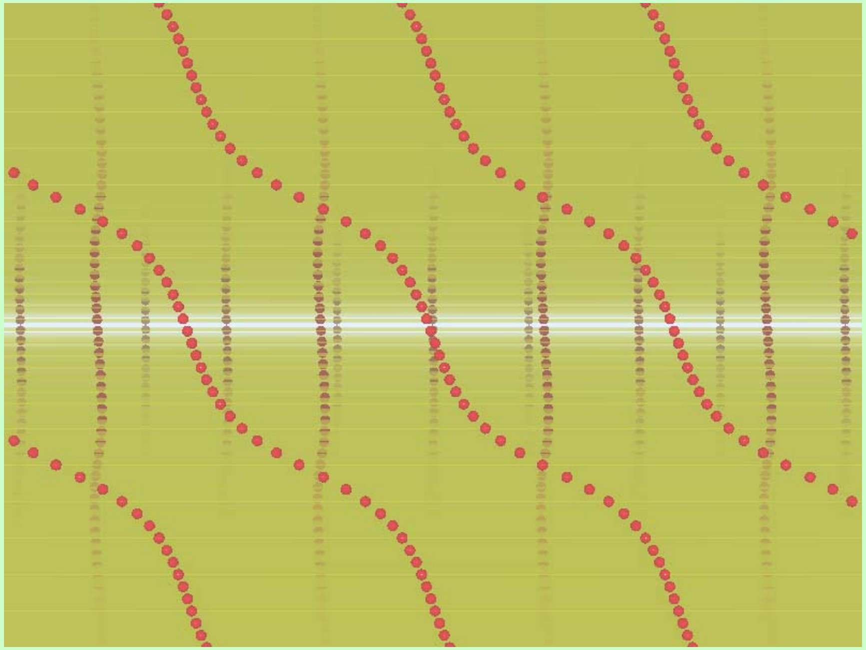


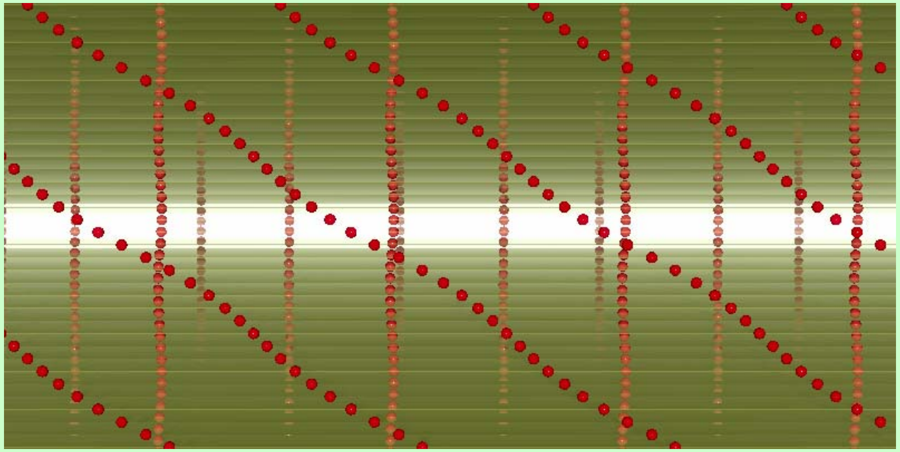


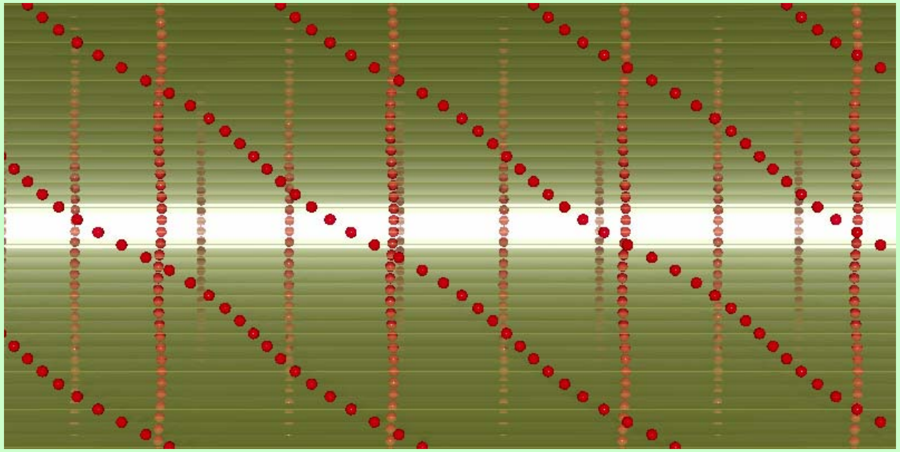


Soliton lattice with increasing B_x









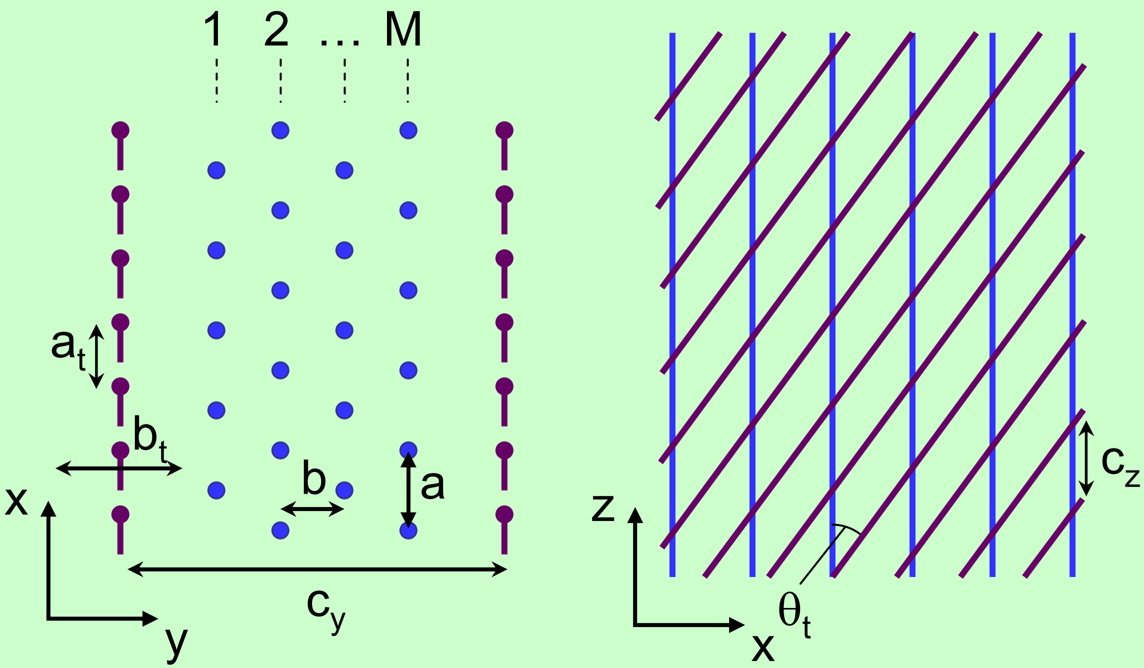
Composite Lattices and Tilted Lattice at large tilt angles

Phase diagram at moderate α

Argonne NATIONAL LABORATORY

Composite Lattices

Daemen et al. 1993, Sudbø et al. 1993, Sardella 1997



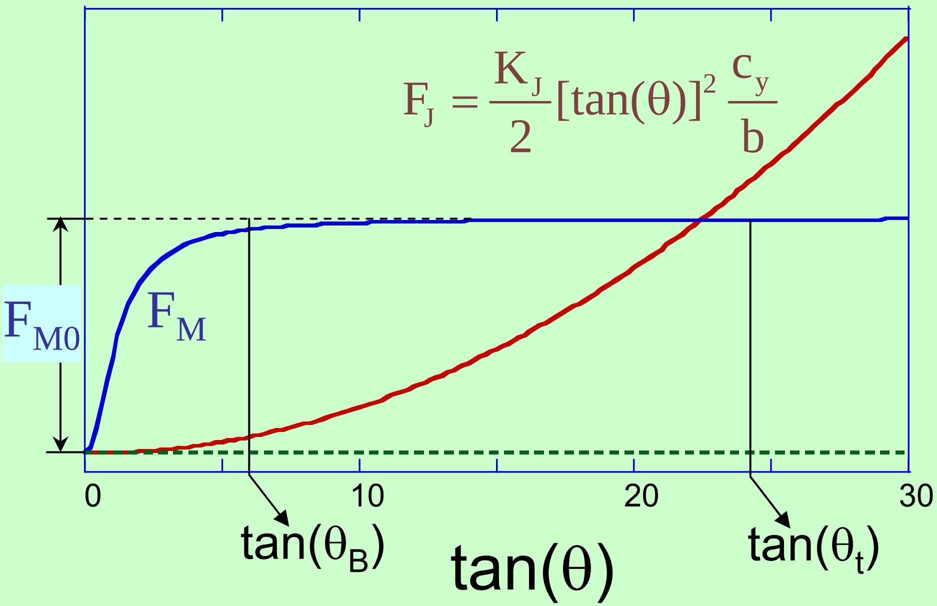
- Dense-lattice case $a < \lambda$
- Tilt angle of field $1 \ll \tan\Theta \ll \gamma$

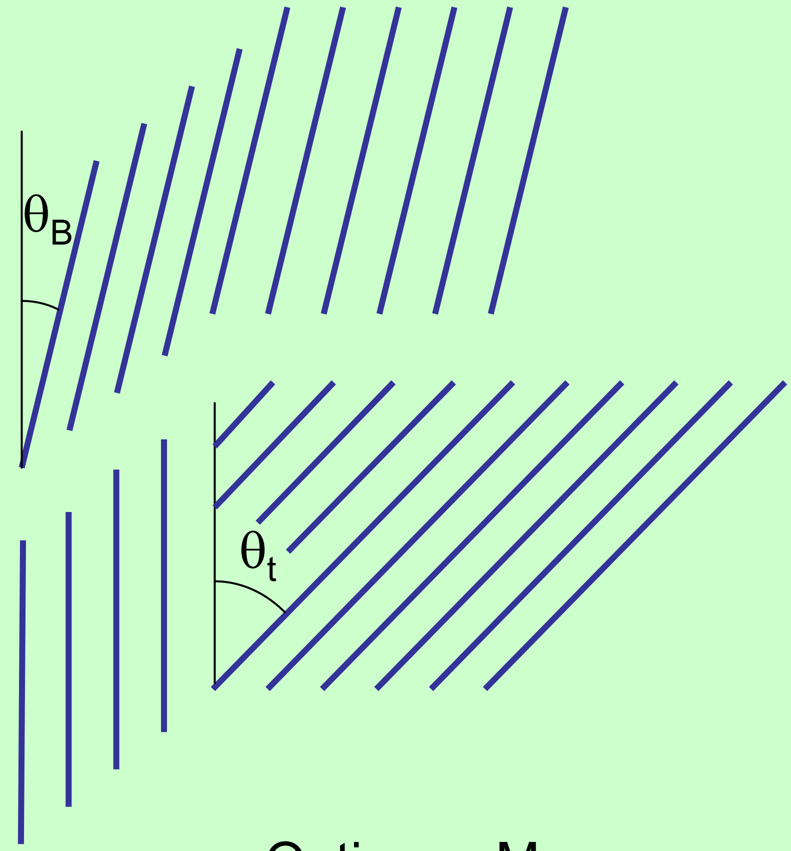
For fixed field: two independent parameters: M and $r = a/a_t$

$$E = \min_{M,r}[E(M,r)]$$

Why composite lattice may be better?

Energy per tilted row





$\tan(\theta_t)=(M+1)\tan(\theta_B)$

Energy per row

$$F(M) = \frac{1}{M+1}\left((M+1)^3 \frac{K_J}{2}\tan^2\theta_B + F_{M0}\right)$$

Optimum M

$$M+1 \approx \left(\frac{F_{M0}}{K_J \tan^2\theta_B}\right)^{1/3}$$

Argonne NATIONAL LABORATORY

Estimates

Number of straight rows M in between tilted rows

$$M+1=\left(\frac{0.24\Phi_0\gamma^2 B_z}{4\pi\lambda^2 B_x{}^2}\right)^{1/3} \gg 1$$

Energy

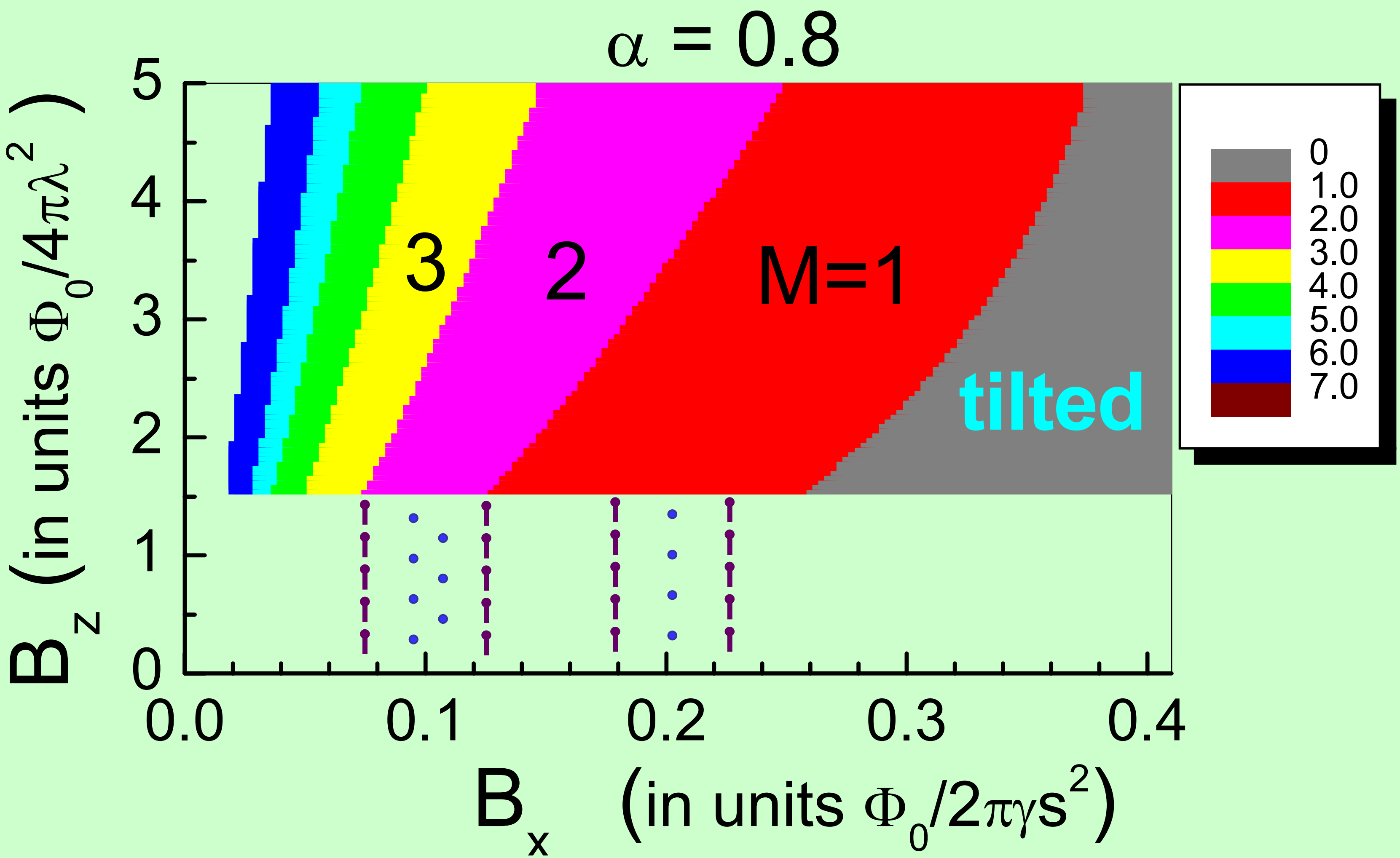
$$F(B_x,B_z)-F(0,B_z)\approx\frac{\varepsilon_0}{2\pi\lambda^2}\left[\frac{B_x}{\gamma B_z}\right]^{2/3}\left[\frac{2\pi\lambda^2 B_z}{\Phi_0}\right]^{1/3}$$

Transition composite → tilted lattice $E_{M=1} = E_{tilt}$

$$B_{x,t}(B_z)\approx\gamma\sqrt{\frac{B_z\Phi_0}{4\pi\lambda^2}}$$

Argonne NATIONAL LABORATORY

Phase diagram
using analytical energies



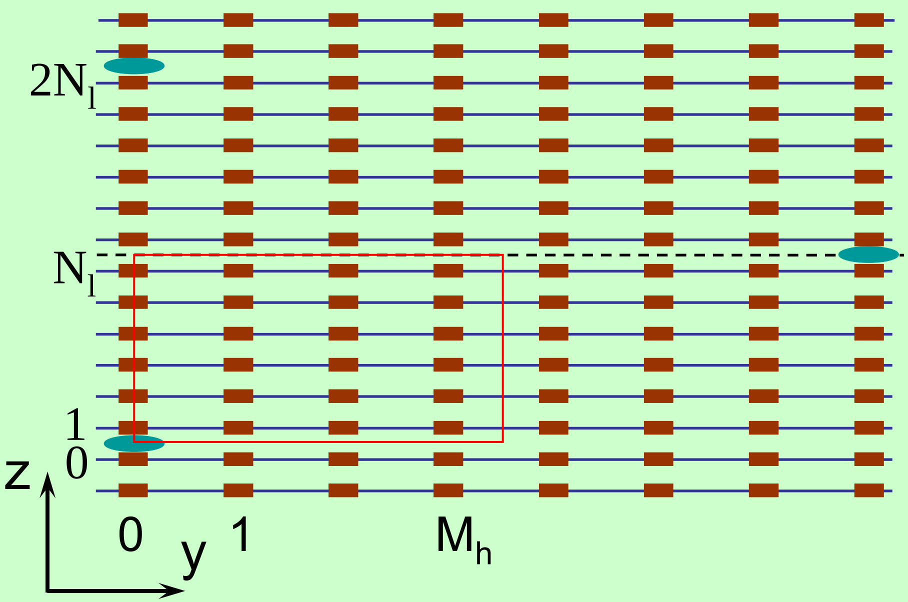
Numerical exploration of lattice states

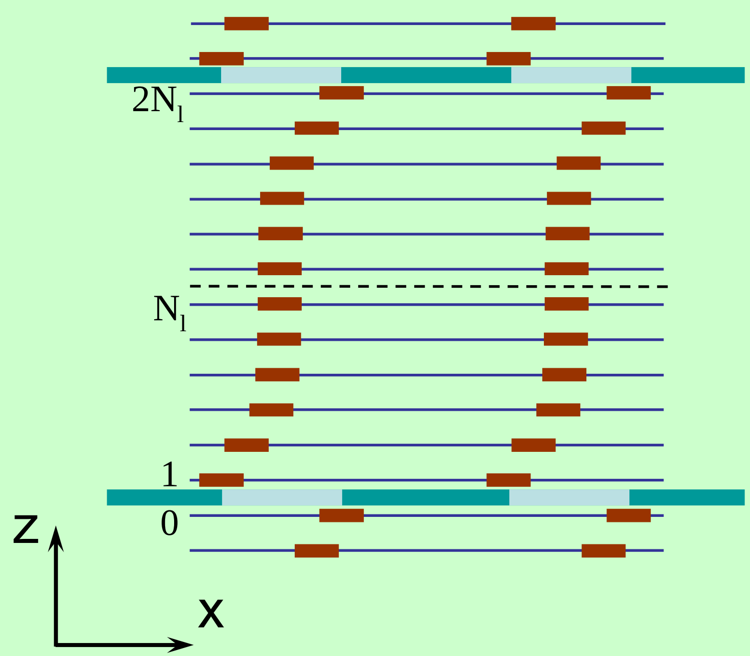
Numerical minimization of energy of unit cell with respect to
- row displacements $u_{n,l}$
- phase $\phi_n(y)$

Long-range+local

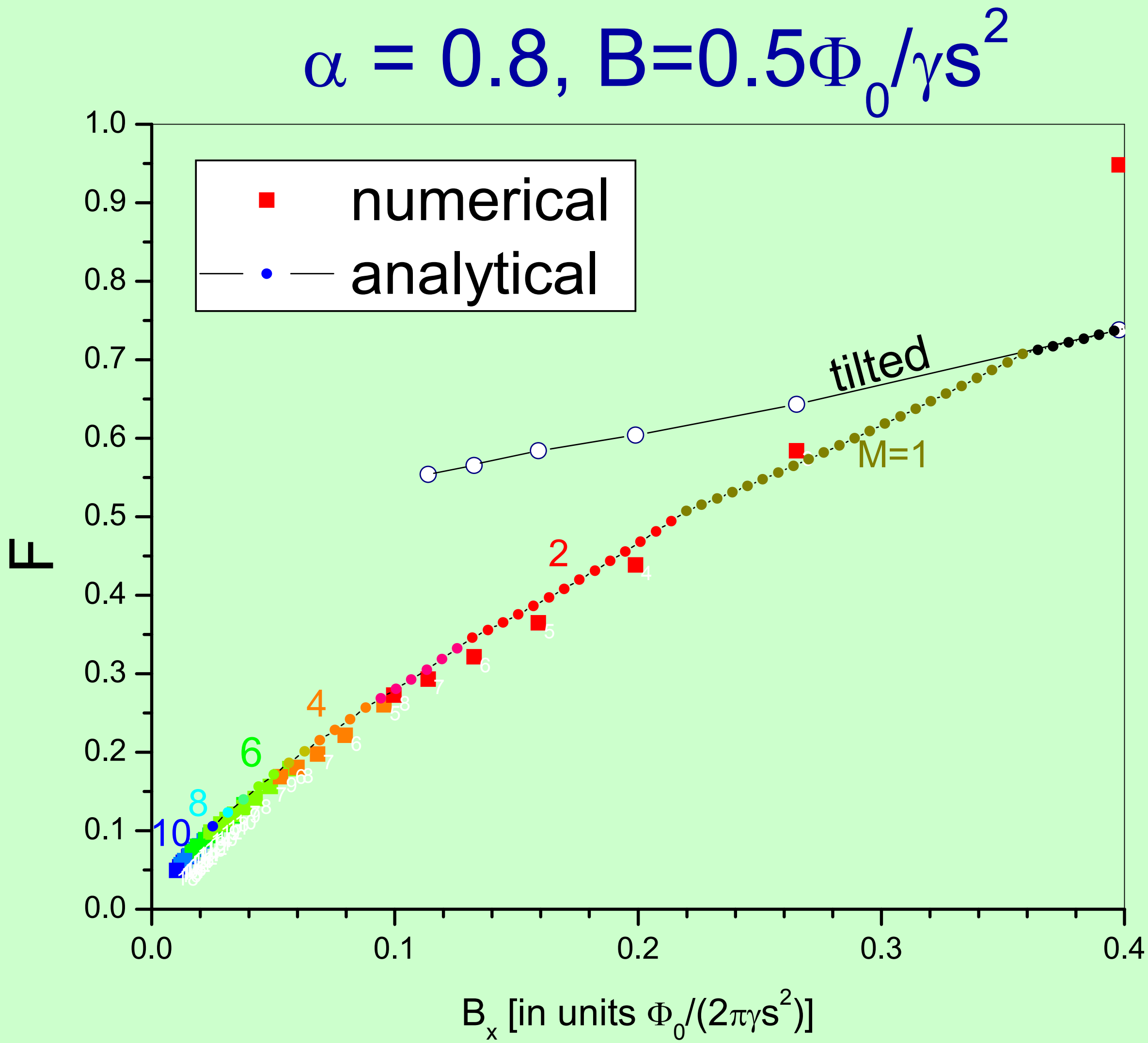
$$E[\phi,u] = E_{phase}[\phi] + E_M[u] + E_{shear}[u] + E_J[\phi,u]$$

Cell $2N_l \times (2M_h+1)$

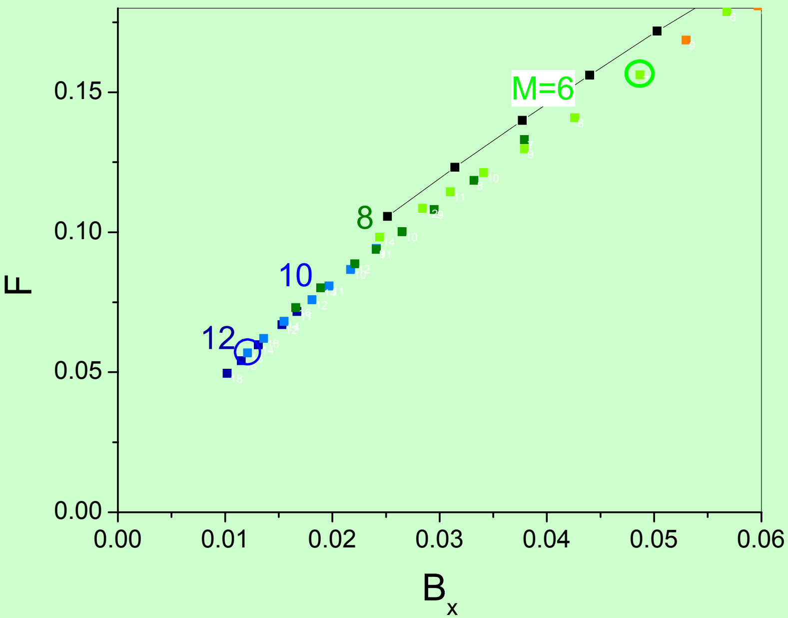


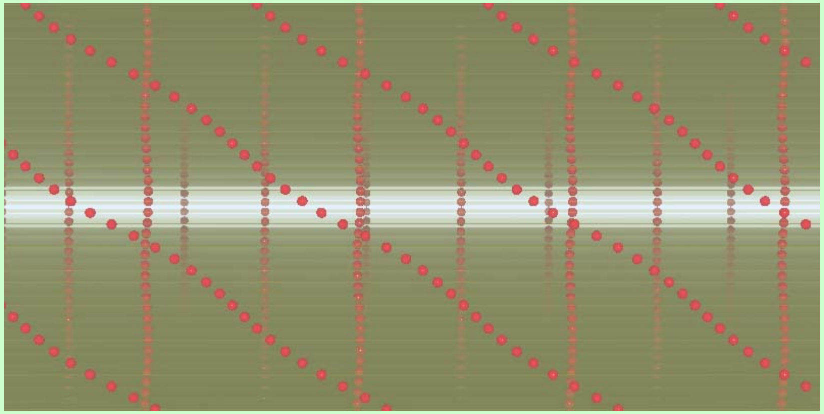


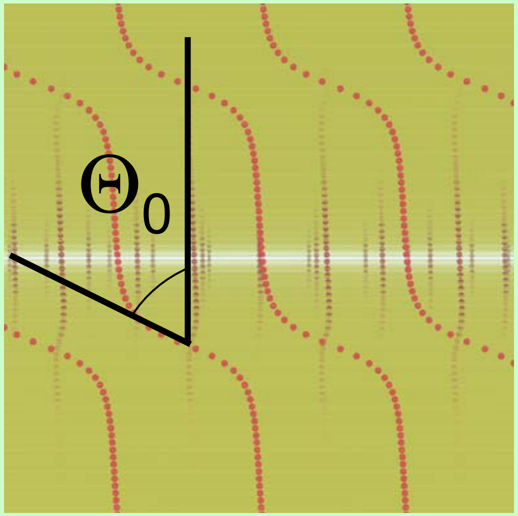
Comparison of analytical and numerical results

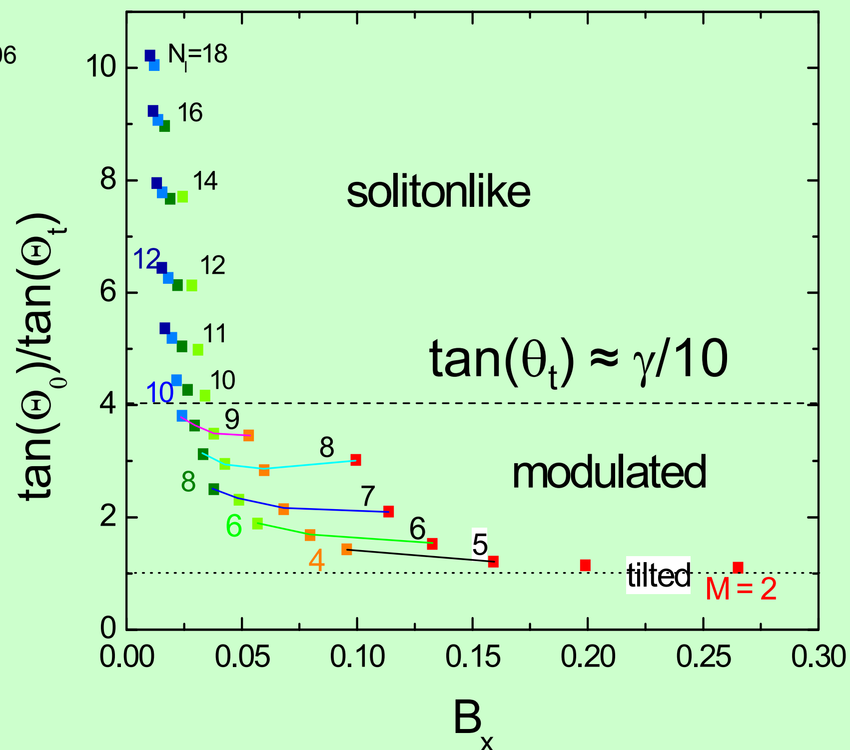


Crossover from tilted to soliton rows

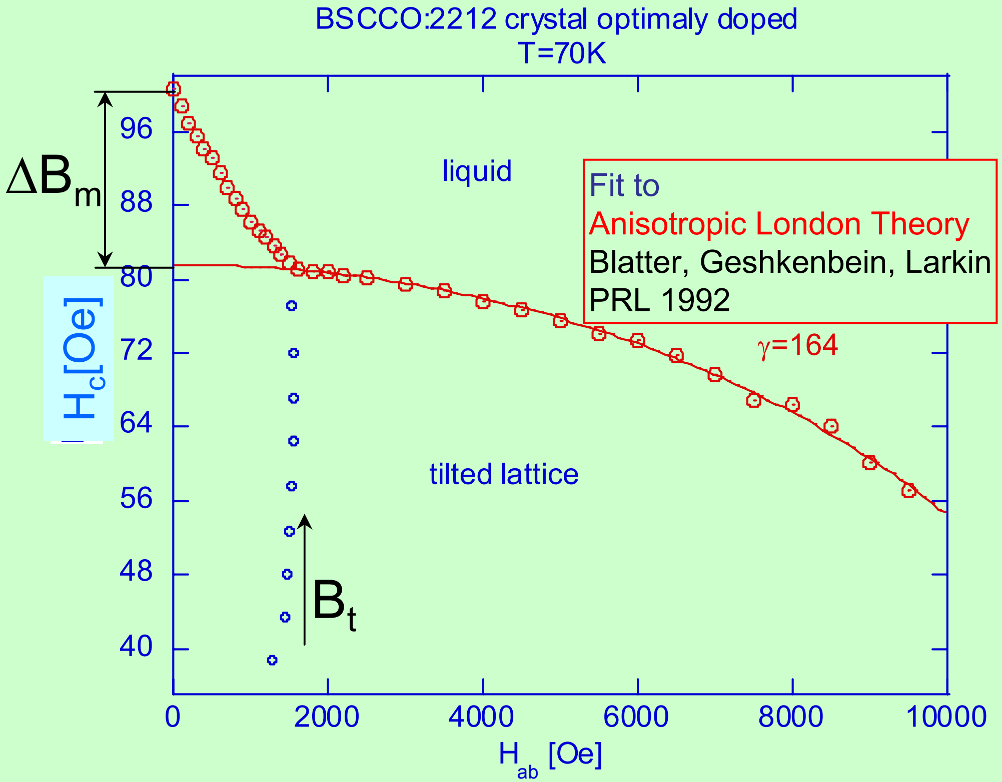








BSCCO phase diagram



M. Konczykowski *et al.*, PRL 2006

Parameters

λ_{ab}= 300nm and γ = 200 (α =0.96) small ?

give

$B_t \approx 1.7$ kG at B_z = 80G

role of fluctuations ?

$$\Delta B_m = \frac{E_M}{\Delta M} \approx 30 \text{ G}$$

magnetic-coupling shift

Konczykowski *et al.*, 2000

Mircović *et al.*, 2001

Tokunaga *et al.*, 2002

$$E_M \approx -\frac{9\Phi_0^{\ 2}}{256\pi^5\lambda^4}\exp\left(-\frac{8\pi^2 c_L^2}{3}\right)$$

Argonne NATIONAL LABORATORY

Summary

- Chain transitions
  - Transition crossing → tilted at moderate B_z (1-3 G)
    - Intermediate states
  - Transition [kinked lines]→[crossing chain] at very small B_z (0.1-0.3 G)
    - Finite anisotropy range $0.5 < \alpha < 0.65$
    - Density jump
- Crossover Josephson vortex-soliton at $\alpha \sim 0.5$
- Composite-lattice phase diagram for $\alpha \sim 1$
  - Solitons → Composite → Tilted

Argonne NATIONAL LABORATORY