Modeling layered HTSC with short-range attractive vortex-vortex interaction potentials using Monte Carlo approach

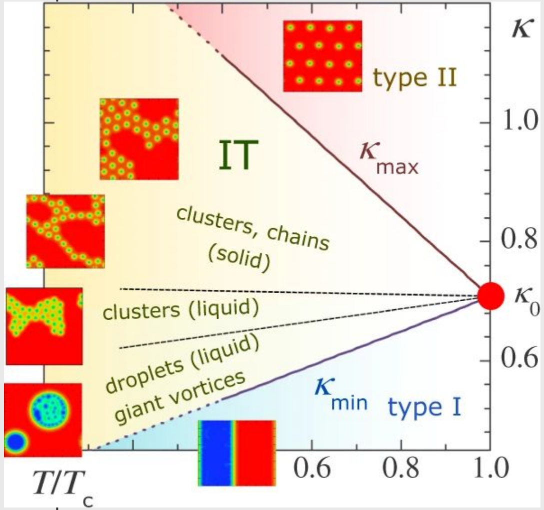
Lenkov V. P., Maksimova A. N., Moroz A. N., Kashurnikov V. A.

NRMU MEPhI, Dubna, 30 October 2024

MEPhI

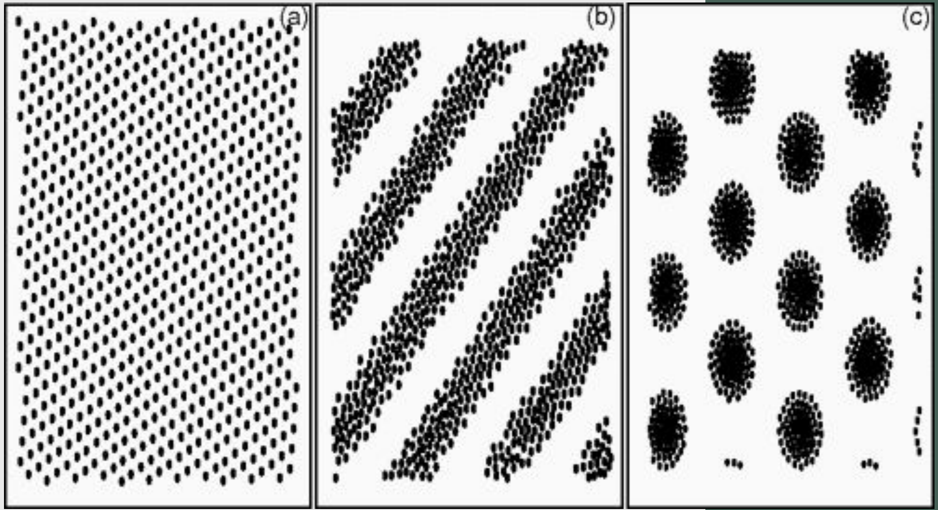
National Research
Nuclear University

Introduction

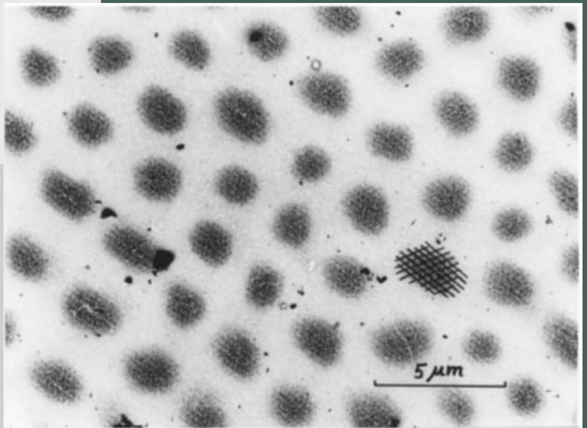


[1]Vagov, A., Wolf, S., Croitoru, M.D. et al. Commun Phys 3, 58 2020

$$\kappa = \frac{\lambda}{\xi} \approx \frac{1}{\sqrt{2}}$$



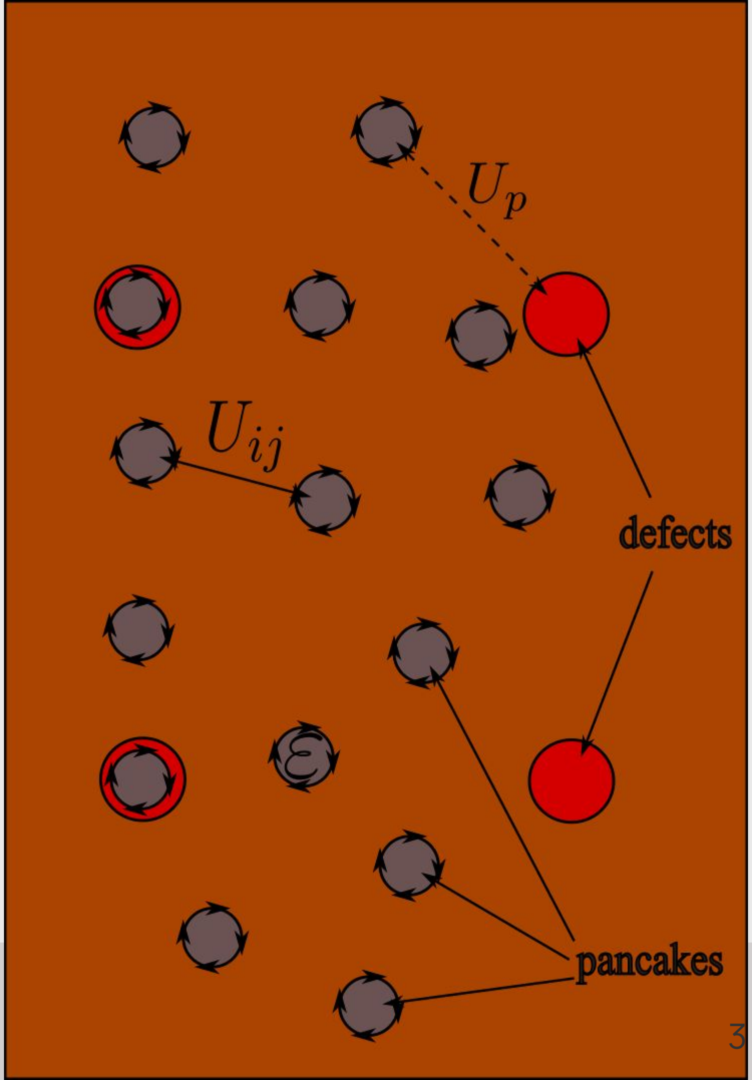
[2]Xu, X. B.; Fangohr, H.; Ding, S. Y.; Zhou, F.; Xu, X. N.; Wang, Z. H.; Gu, M.; Shi, D. Q.;Dou, S. X. Phys. Rev. B 2011



[3]Brandt, E.H., Das, M.P. J Supercond Nov Magn 24, 57–67 2011

The geometry of the model

- 2D plate, perpendicular to which the external field H is directed
- Periodic boundaries
- Pairwise interactions
- Square lattice of defects



The Gibbs free energy

$K_0\left(\frac{r_{ij}}{\lambda}\right)$ - the Macdonald function

δ - layer thickness

ε - vortex self-energy

U_h - energy of interaction with field

U_{ij} - vortex-vortex interaction energy

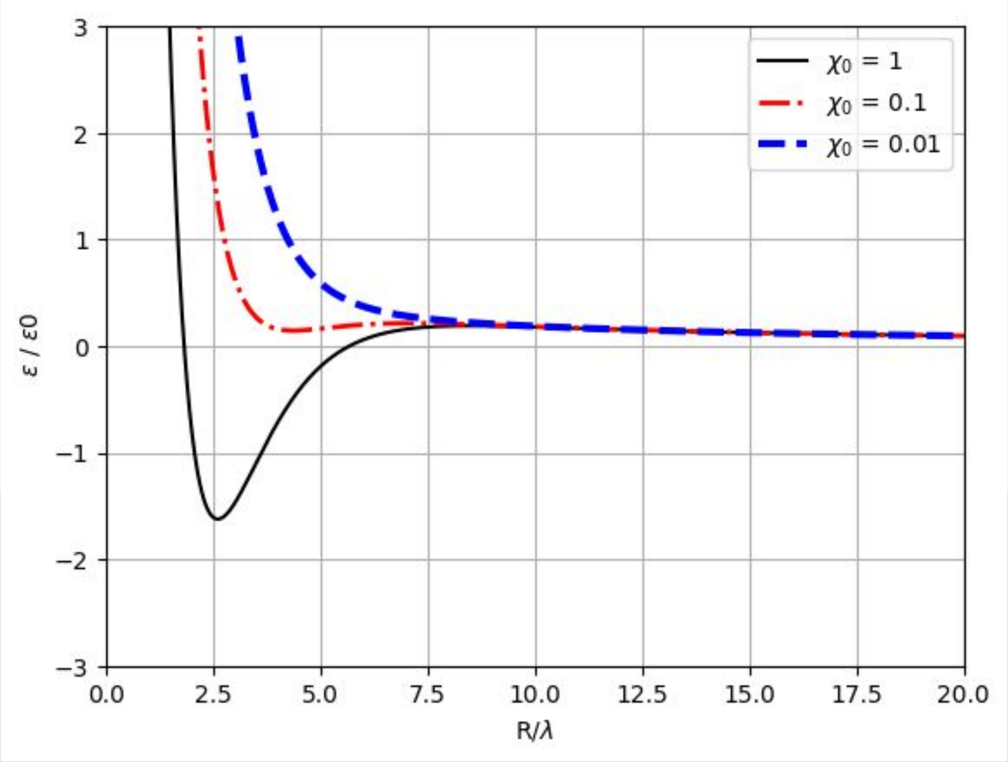
Φ_0 - fluxoid quantum

$$G=\sum_i\left(\frac{1}{2}\sum_{j\neq i}U_{ij}+\varepsilon+U_h+\sum_{j_{def}}U_p\left(r_{ij_{def}}\right)\right)$$

$$U_{ij}=U_0K_0\left(\frac{r_{ij}}{\lambda}\right)\quad U_0=\frac{(\vec{\Phi_0})_1(\vec{\Phi_0})_2}{8\pi^2\lambda^2}\delta$$

$$U_h=-\frac{\Phi_0 H}{4\pi}\delta\quad \varepsilon=\delta\left(\frac{\Phi_0}{4\pi\lambda}\right)^2\ln\left(\frac{\lambda(T)}{\xi(T)}+0.52\right)$$

Ferromagnetic potential

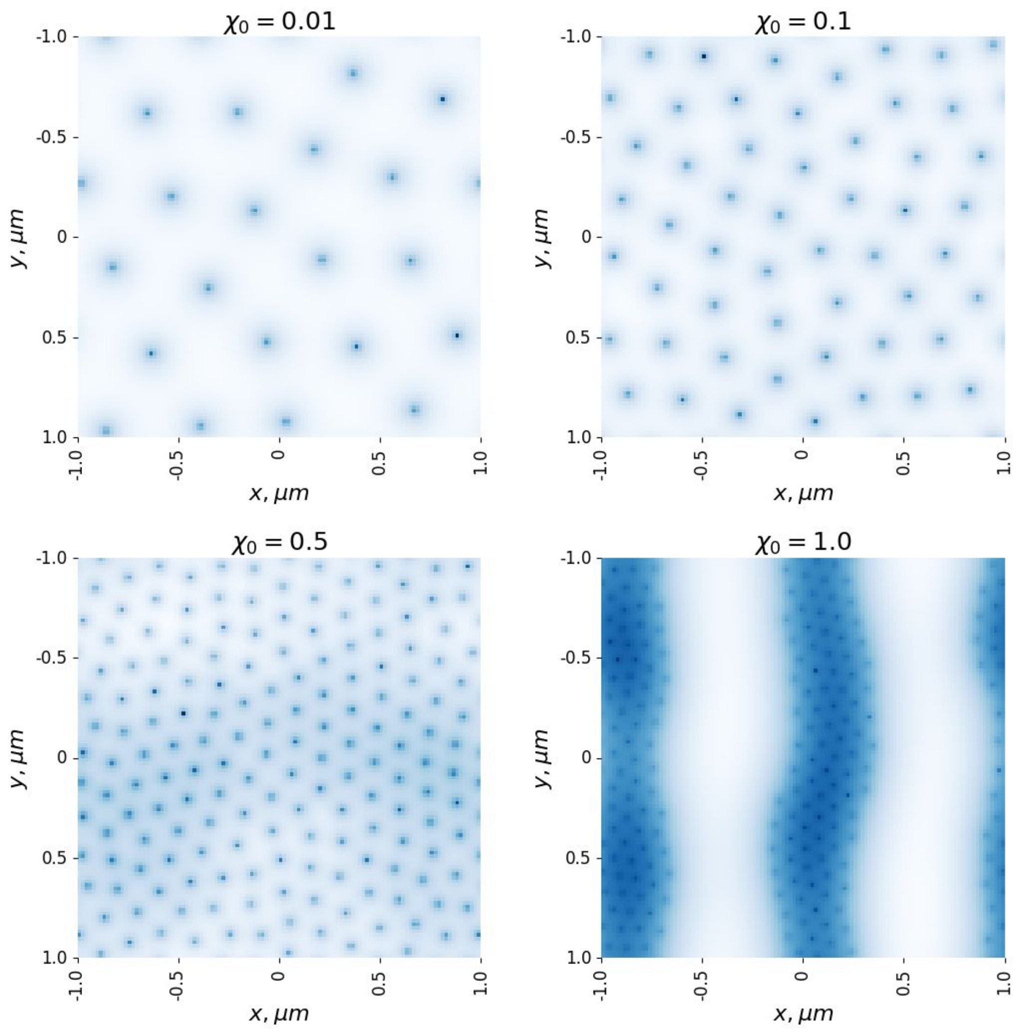


- Conflicting impacts of ferromagnetic and superconducting subsystems
- Effective attraction due to ferromagnetic properties
- The interaction potential changes with susceptibility χ_0

Field distribution at different susceptibility χ_0

- triangular lattice for low susceptibility
- shapeless clusters - smooth transition
- stripes in purely ferromagnetic superconductors

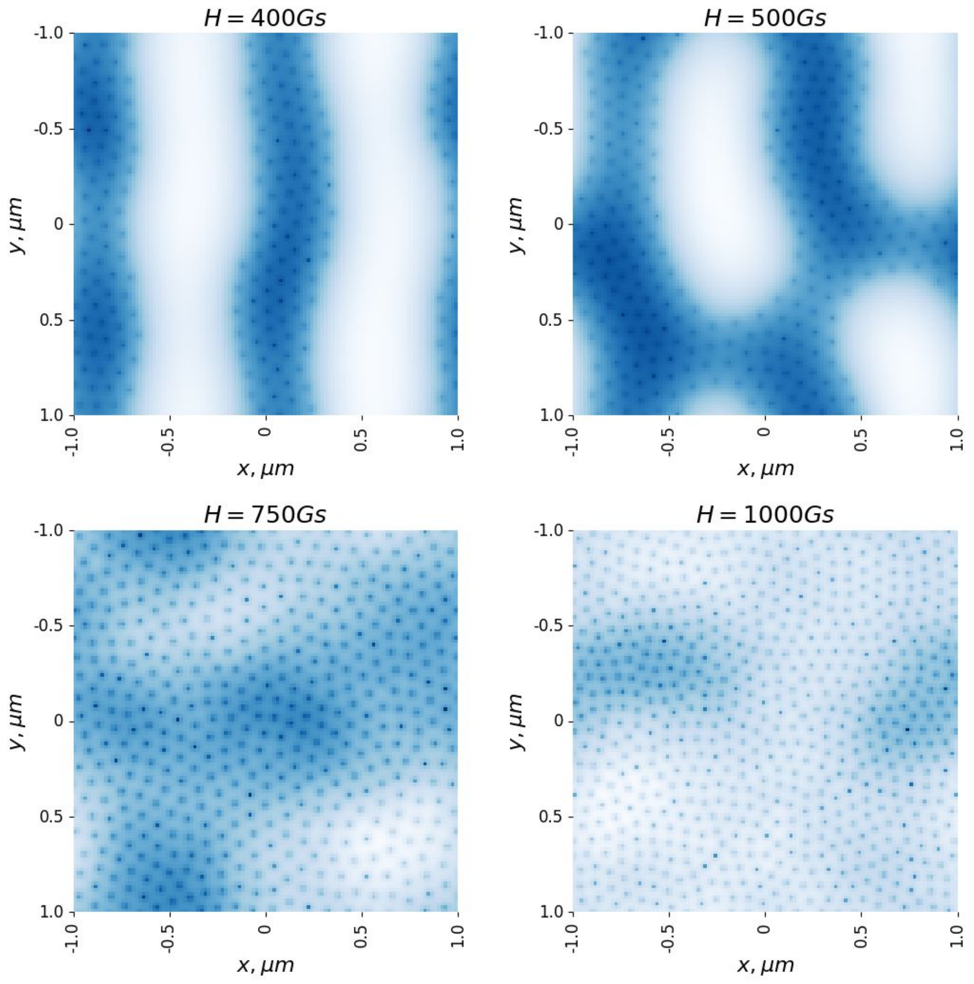
[H = 400 Gs, T = 1K]



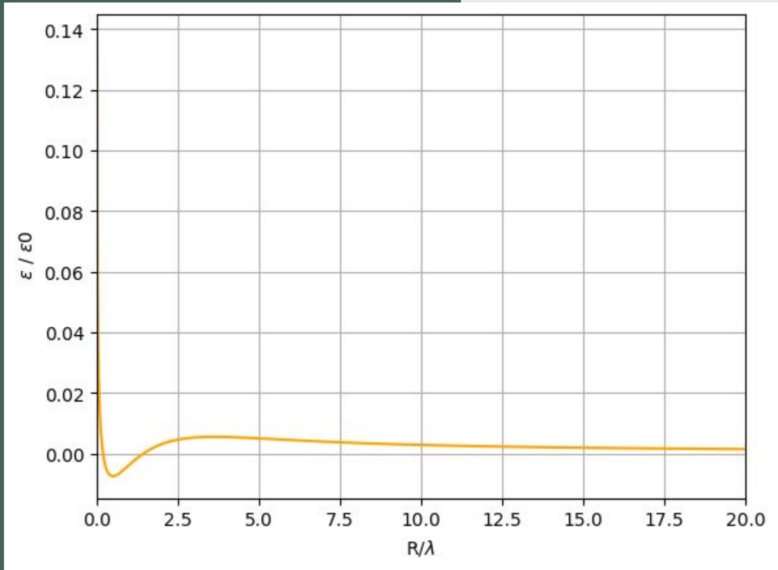
Field distribution at different values of H

- Stripes and chains at lower Hs
- the influence of clusters on the distribution is less noticeable at high fields

[χ_0=1.0, T= 1K]



Intertype potential



This potential, like the ferromagnetic one, has one maximum and one sharp minimum.
The energy of vortex-vortex interaction was set as follows:

$$U(r) = (-q)\left(\ln\frac{r}{r+\lambda} + k\exp\left(-\frac{r}{\xi}\right)\right)$$

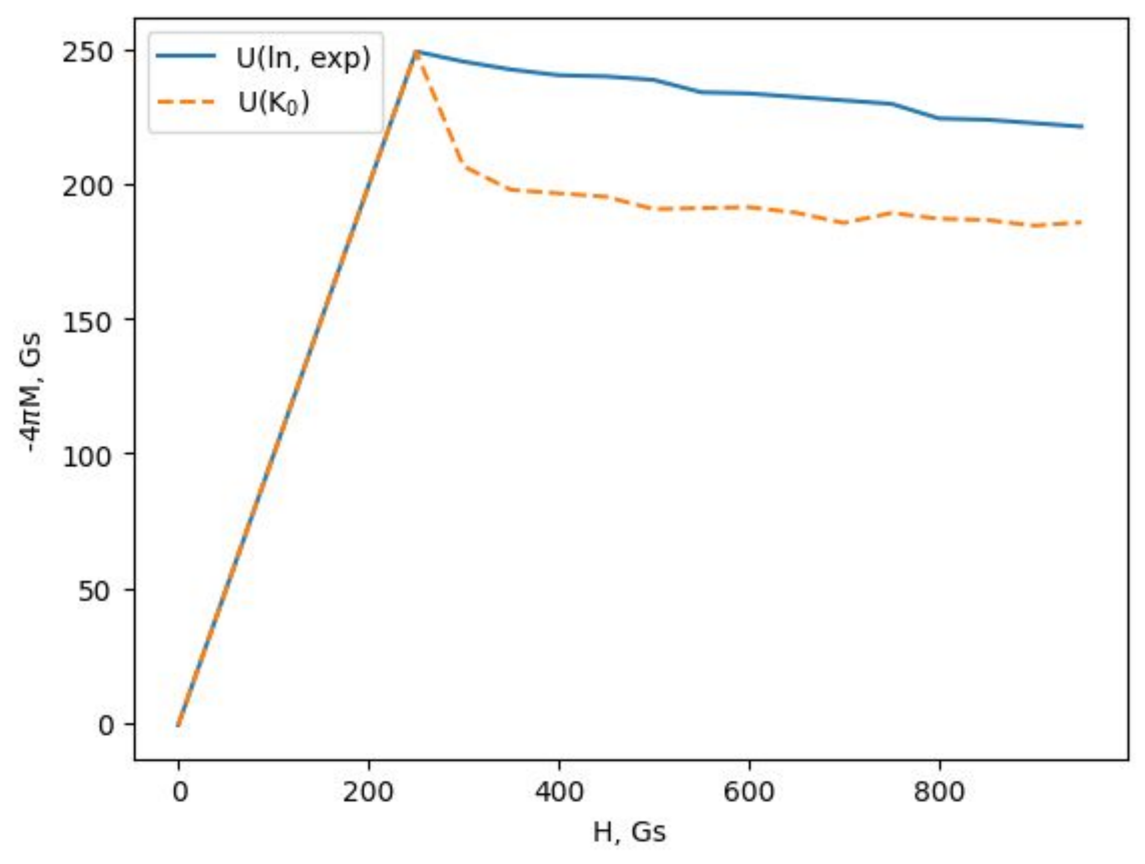
k, q - model parameters that were selected so that the repulsion corresponded to the potential of a conventional superconductor

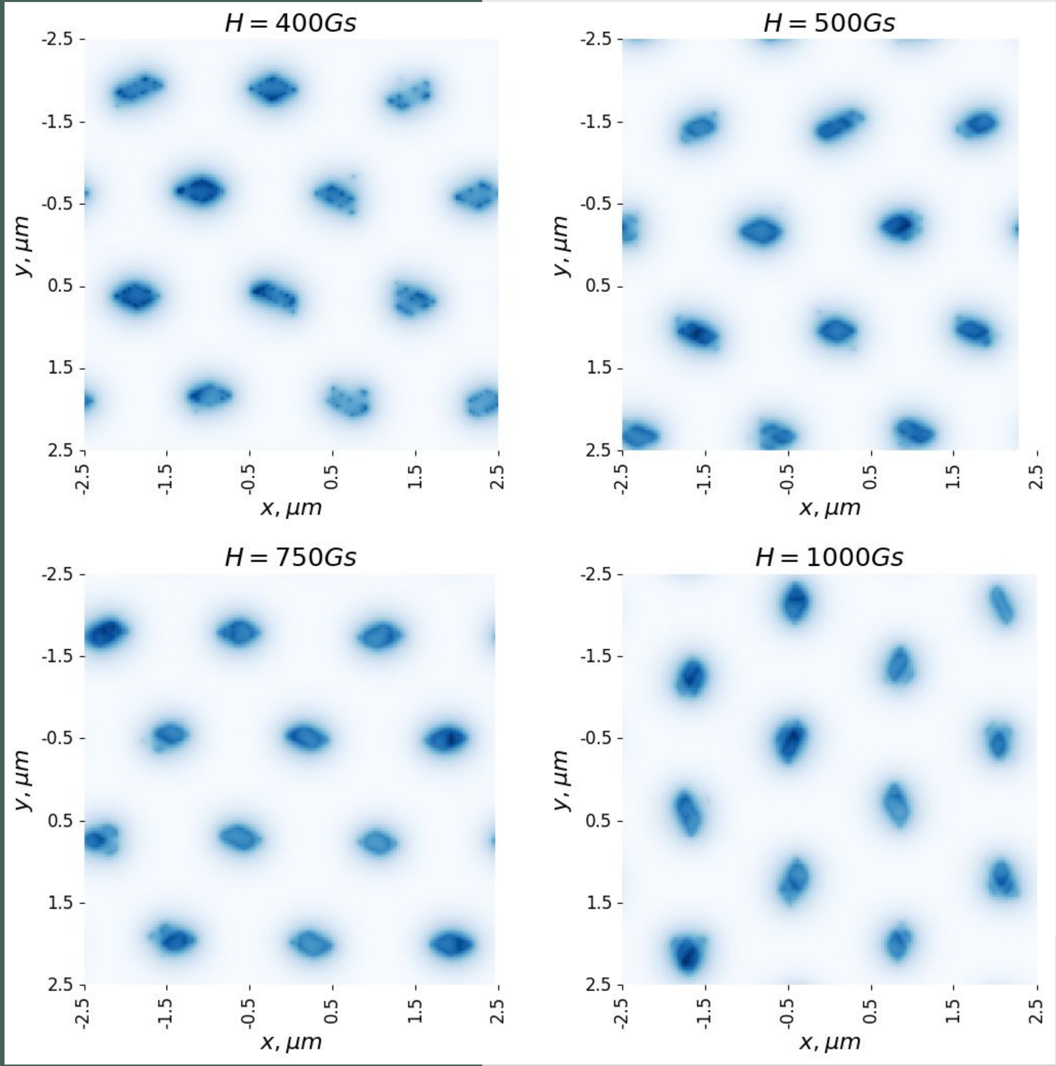
Results

The magnetization curves of the intertype and conventional HTSC(Nd=0):

- the same maximum at same GL parameters

- cluster structure is more stable





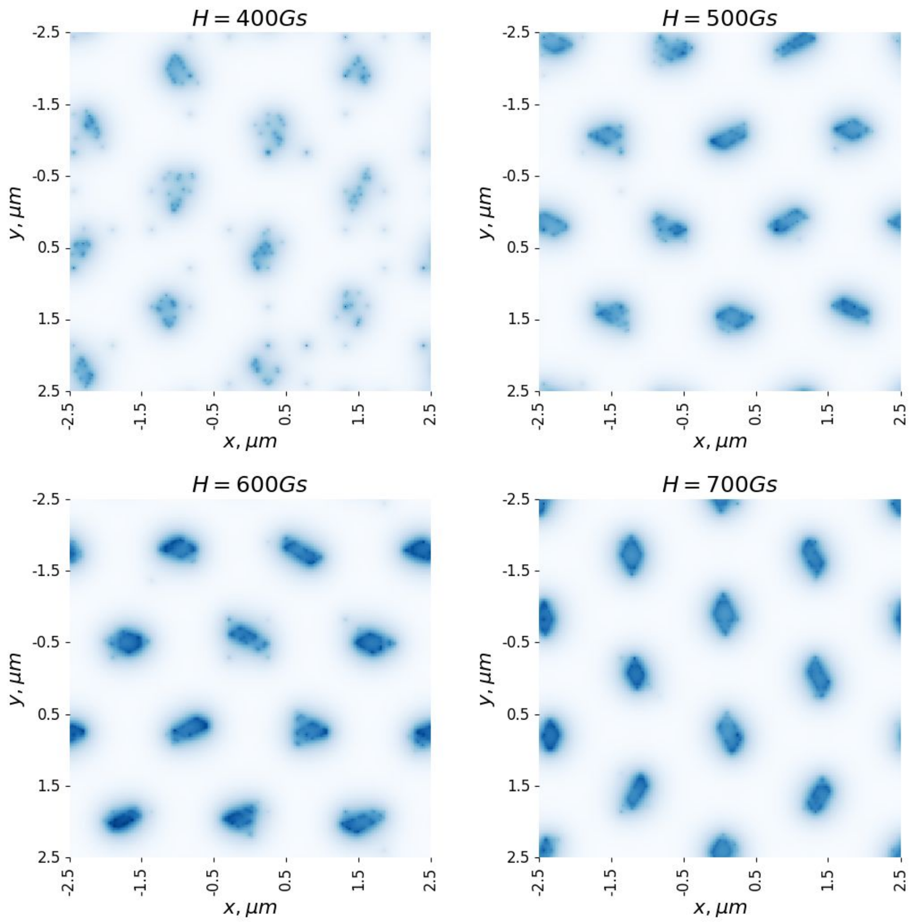
Field distribution

- Forms of triangles, diamonds
- Changes quite slightly
- At 1K magnetic flux is “frozen”

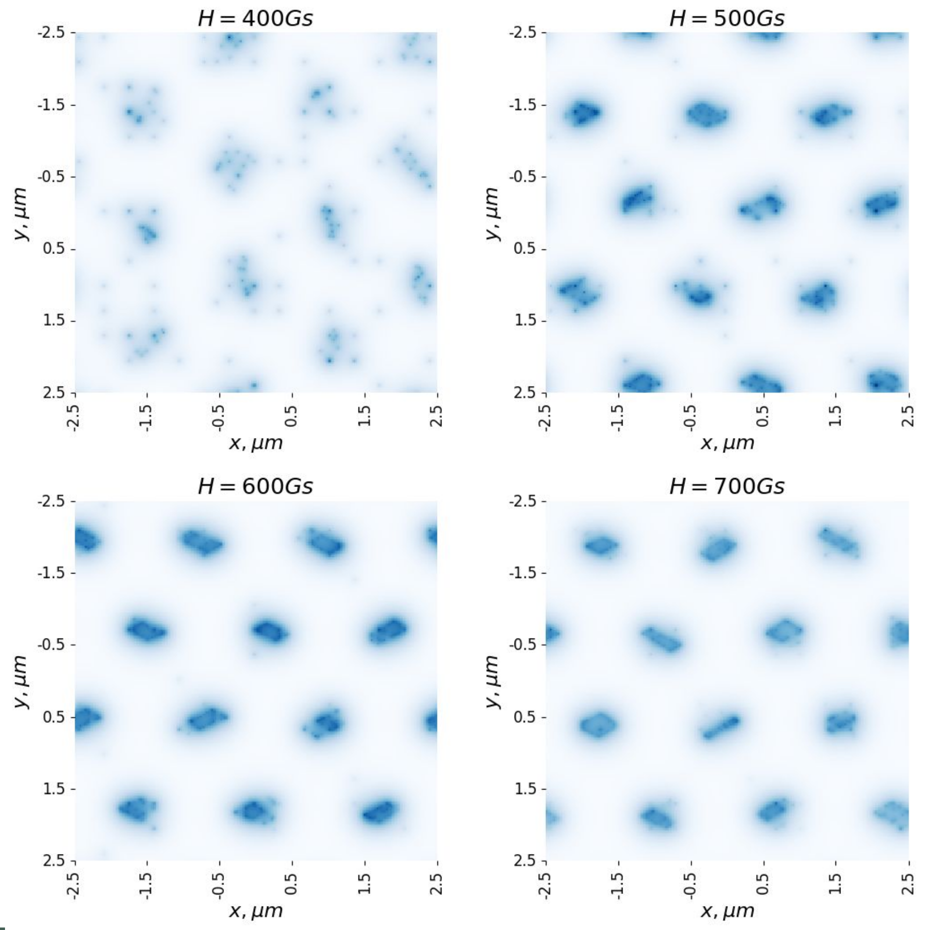
[Nd = 0, T=1K]

Nd = 100

Nd = 225

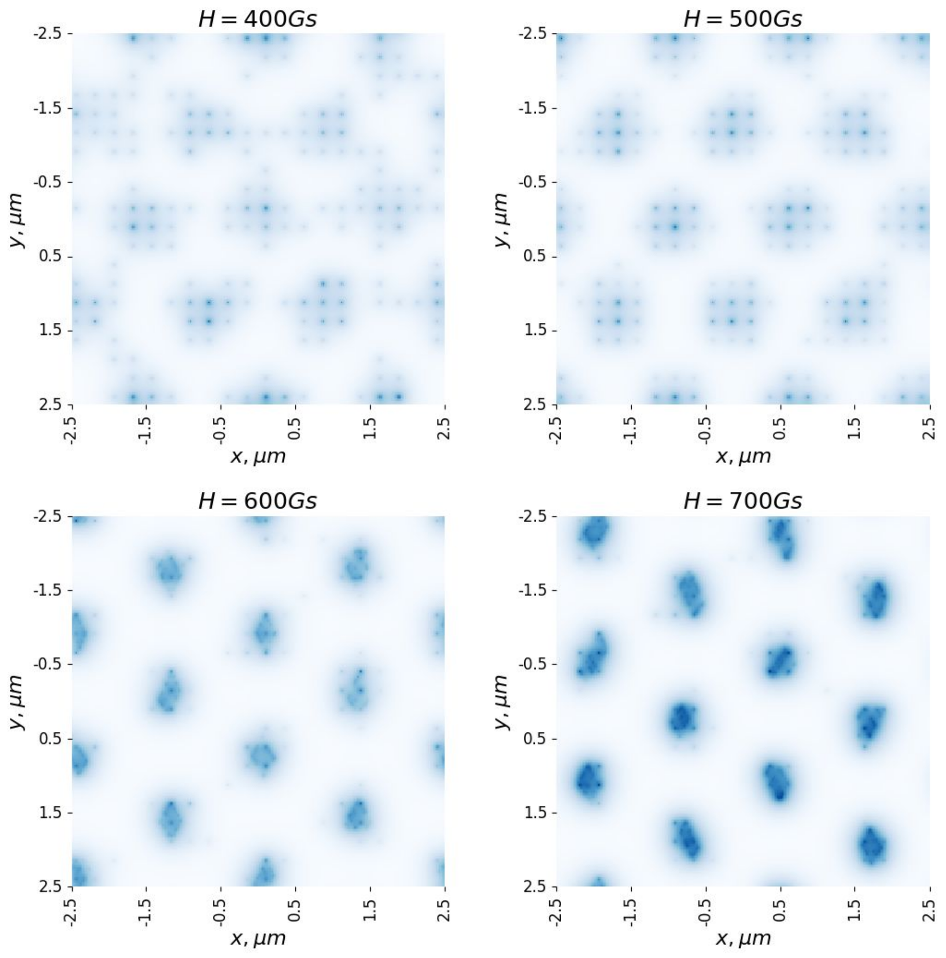


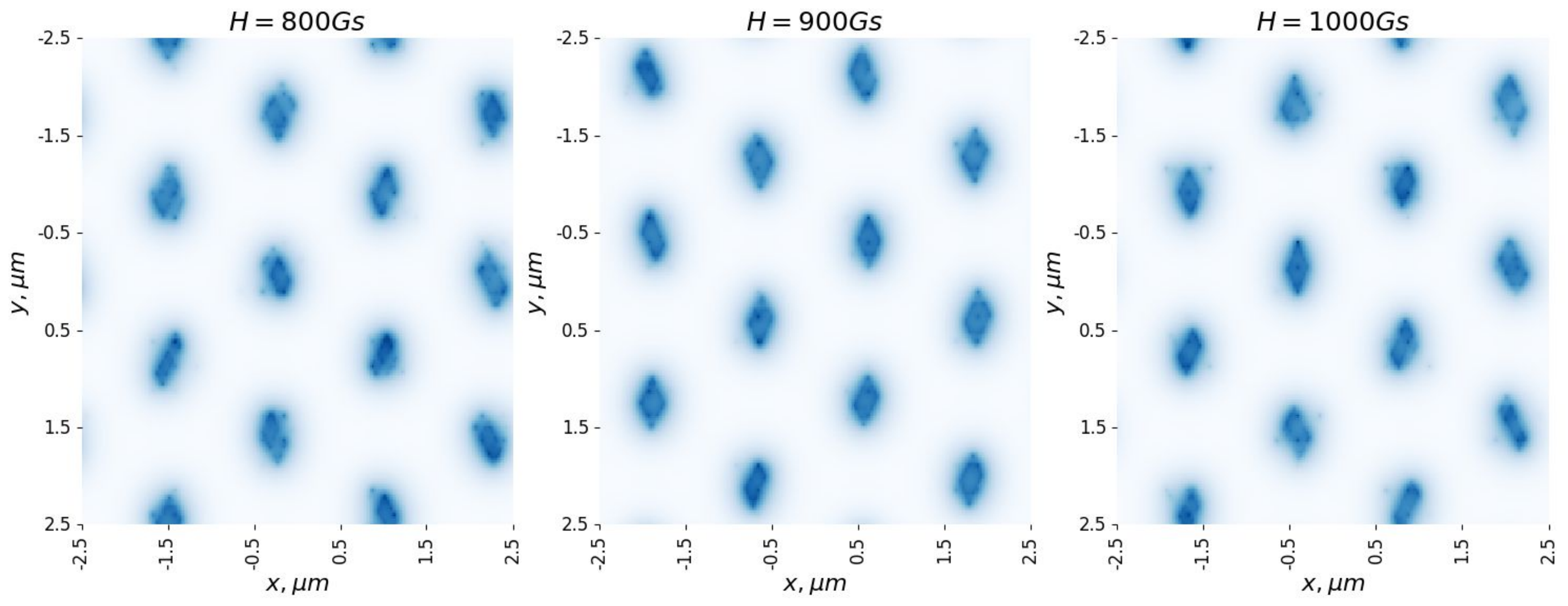
H = 400Gs
H = 500Gs
H = 600Gs
H = 700Gs
y, μm
x, μm
-2.5
-1.5
-0.5
0.5
1.5
2.5



H = 400Gs
H = 500Gs
H = 600Gs
H = 700Gs
y, μm
x, μm
-2.5
-1.5
-0.5
0.5
1.5
2.5

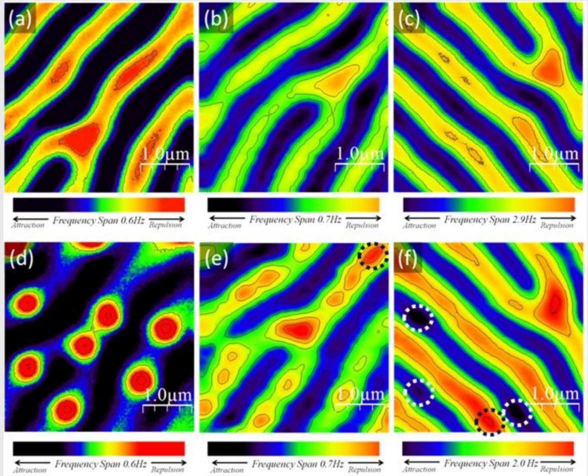
Field distribution, Nd = 400




$H = 800Gs$
$H = 900Gs$
$H = 1000Gs$
$y, \mu m$
$x, \mu m$
-2.5
-1.5
-0.5
0.5
1.5
2.5

Conclusion

- Monte Carlo method is applicable to ferromagnetic and intertype superconductors
- The vortex structure in ferromagnetic superconductors strongly depends on susceptibility, and there is a tendency to form stripes
- The cluster structure of intertype superconductors is quite stable both to the field and to defects in the material



[5]Di Giorgio, C., Bobba, F., Cucolo, A. et al. Observation of superconducting vortex clusters in S/F hybrids. Sci Rep 6, 38557 2016

References

[1]Vagov, A., Wolf, S., Croitoru, M.D. et al. Commun Phys 3, 58 2020

[2]Xu, X. B.; Fangohr, H.; Ding, S. Y.; Zhou, F.; Xu, X. N.; Wang, Z. H.; Gu, M.; Shi, D. Q.;Dou, S. X. Phys. Rev. B 2011

[3]Brandt, E.H., Das, M.P. J Supercond Nov Magn 24, 57–67 2011

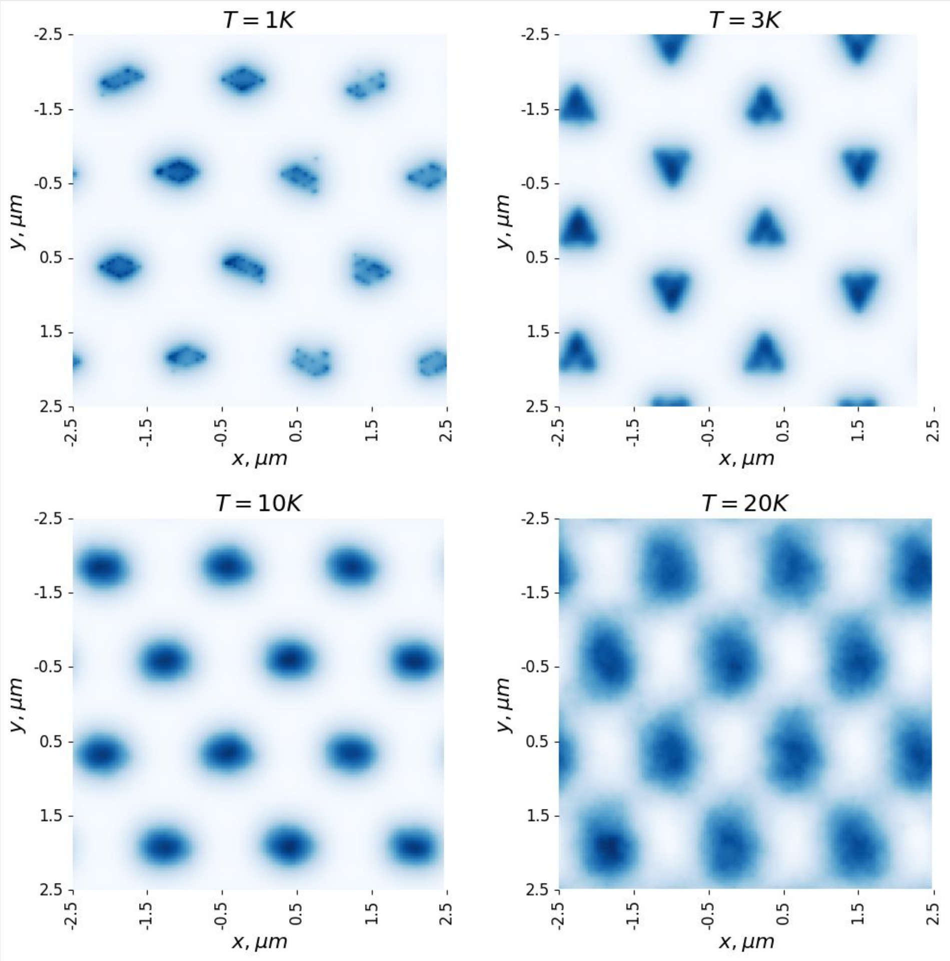
[4] Lin, S. Z., Bulaevskii, L. N., & Batista, C. D. (2012). Vortex dynamics in ferromagnetic superconductors: Vortex clusters, domain walls, and enhanced viscosity. Physical Review B—Condensed Matter and Materials Physics, 86(18), 180506

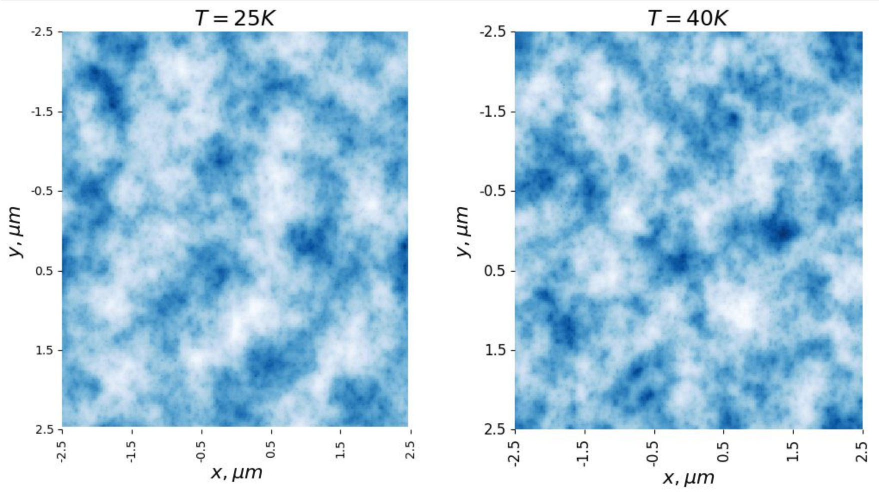
[5]Di Giorgio, C., Bobba, F., Cucolo, A. et al. Observation of superconducting vortex clusters in S/F hybrids. Sci Rep 6, 38557 (2016).

The research was done under support of MEPhI Program Priority-2030

Thank you for your attention!

Temperature dependance



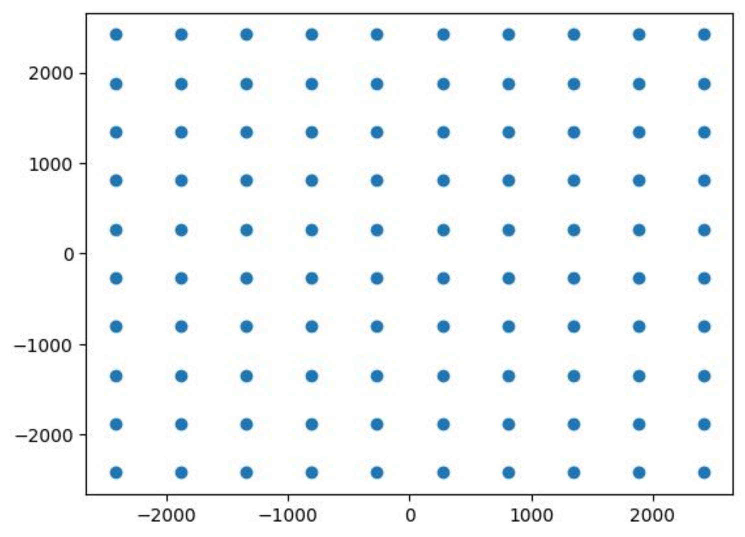


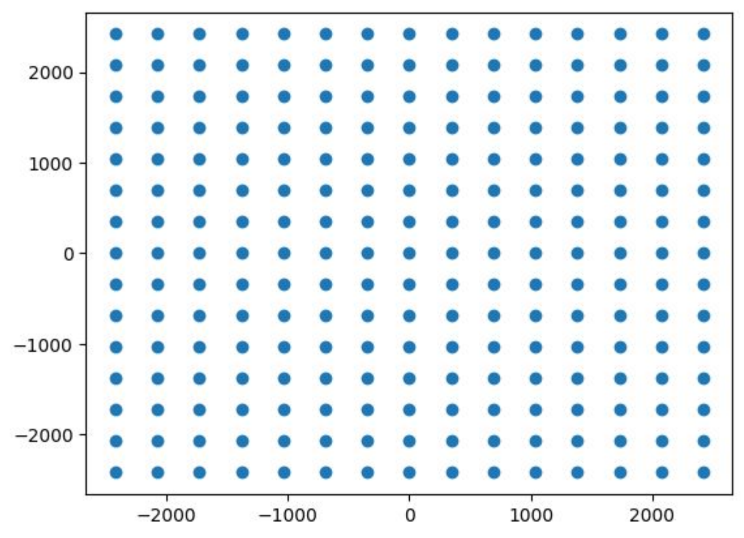
$$\lambda(T) = \lambda_0 \left(1 - \left(\frac{T}{T_c}\right)^{3.3}\right)^{-\frac{1}{2}},$$

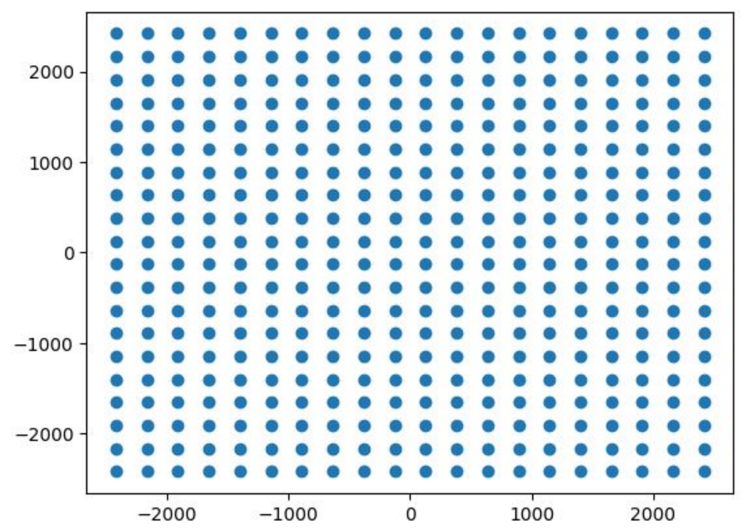
$$\lambda_0 \equiv \lambda(T = 0),$$

$$\xi(T) = \xi_0 \left(1 - \left(\frac{T}{T_c}\right)^{3.3}\right)^{-\frac{1}{2}}, \xi_0 \equiv \xi(T = 0)$$

Defect lattices







$$U_p(r) = -\alpha |U_0| \frac{1}{\frac{r}{\xi} + 1} e^{-\frac{r}{2\xi}}$$

Ferromagnetic potential

$$U_a(r) = -\frac{\delta \Phi_0^2 \chi_0 r}{4\pi \left(1 + 4\pi\chi_0\right) \lambda_e^3} K_1 \left(\frac{r}{\lambda_e}\right)$$

$$\Lambda = 2\lambda_e coth \left(\frac{\delta}{\lambda_e}\right)$$

$$U_r(r) = \frac{\Phi_0^2 \delta}{8\pi^2 \lambda_e^2} K_0 \left(\frac{r}{\lambda_e}\right) + \frac{\Phi_0^2}{8\pi\Lambda} \left[H_0 \left(\frac{r}{\Lambda}\right) - Y_0 \left(\frac{r}{\Lambda}\right)\right]$$

$$\lambda_e = \frac{\lambda}{\sqrt{1 + 4\pi\chi_0}}$$