A1

Superconducting Critical Current by Design

Andreas Glatz, Igor Aronson, George Crabtree, Alexei Koshelev, Ivan Sadovsky
Materials Science Science Division, Argonne National Laboratory, Argonne, IL 60439, USA

oscon-scidac.org

Motivation & GL model

OSCon: **Robust optimization of pinning & geometry for high critical currents and resulting energy applications**

- *Critical current determined by long-time evolution of TDGL (to stationary flow)*
- *Dominated by rare events of vortex depinning, avalanches, nucleation and splitting & reconnection*
- *Frequency and duration of pinning/depinning depends on configurations of inclusions*
- *Suitable pinning configurations must be determined using geometry optimization*

Time-dependent Ginzburg-Landau

TDGL equations:

$$\frac{\partial \Psi}{\partial t} = -\frac{\delta \mathcal{F}_{GL}}{\delta \Psi^*}, \quad \frac{\delta \mathcal{F}_{GL}}{\delta \mathbf{A}} = 0$$

In dimensionless units:

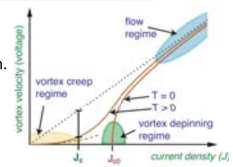
$$u(\partial_t + i\mu)\psi = \epsilon(\mathbf{r})\psi - |\psi|^2\psi + (\nabla - i\mathbf{A})^2\psi + \zeta(\mathbf{r},t)$$
$$\kappa^2 \nabla \times (\nabla \times \mathbf{A}) = \mathbf{J}_n + \mathbf{J}_s + \mathcal{I},$$

Coupled system for ψ and $\mathbf{A}$:
- ψ — complex order parameter characterizing density of Cooper pairs
- $\mathbf{A}$ — vector potential for magnetic field
- ζ and $\mathcal{I}$ — thermal fluctuations
- $\epsilon(\mathbf{r}) = \frac{T_c(\mathbf{r}) - T}{T} \to 0$ for $T \to T_c$ (critical temperature)

Total current: $J = J_s + J_n$ $\quad \mathbf{J} = \mathrm{Im}[\psi^*(\nabla - i\mathbf{A})\psi] - (\nabla\mu + \partial_t \mathbf{A})$

Pinning of Vortices

Motion of vortices leads to dissipation/resistance.
Pinning prevents this motion.
Pinning mechanisms:
- pinning defects
- quenched noise
- geometry/surfaces
- intrinsic/anisotropy



current-voltage characteristics

Realization of pinning in GL

1. **Metallic Inclusions and defects are modeled by T_c modulation: spatial variation of ϵ(r)** [positive in the superconductor, negative in the defect]
2. **Quenched noise** and inclusions or interfaces between **different superconductors** can be modeled by T_c modulation as well
3. **Surfaces, voids, and insulating inclusions** are modeled by open-boundary conditions (or no-current conditions)
4. **Intrinsic pinning** due to layered structures/anisotropy are modeled by spatially dependent diffusion coefficients.

Our simulations (*see also pattern generator on poster A2*) do all of the above and can model:
- ✓ Elliptical, cubic, cross, cylindrical, etc. inclusions
- ✓ Regular grids or randomly placed inclusions
- ✓ Quenched disorder, polycrystalline & Voronoi patterns
- ✓ Different shapes of superconducting domains
- ✓ Anisotropic superconductors

Critical current & optimization

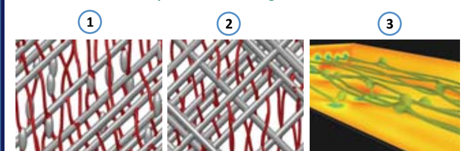
- ➢ Critical current depends strongly on the pinning in the superconductor
- ➢ Using the pattern generator the critical current for a fixed pinning configuration is obtained
- ➢ The latter is defined by several parameters, e.g., size & concentration of defects, angle & diameter of columnar defects, etc. and any combination thereof

Task: Find the values for each of the defining pinning parameter in order to achieve the best critical current!

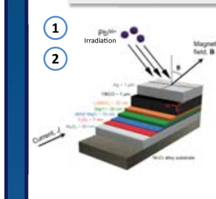
- ➢ A typical realistic system has about **10 pinning parameters → sophisticated optimization required (→ *poster A2*)**

Critical current by design: *examples*

Here three examples with only one or two parameters:
1. **Nanorods + columnar defects**
2. **Columnar defects at different angles**
3. **Point defects in parallel field configuration**

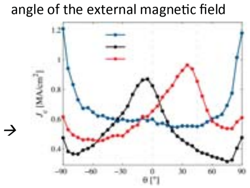


Experimental motivation



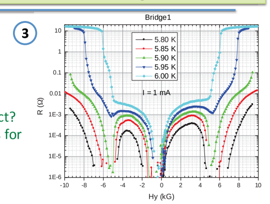
Commercial superconducting tape with nanorod inclusions is irradiated by heavy ions at 45 deg → understanding of the critical current depending on the angle of the external magnetic field

Effect of defects not additive →



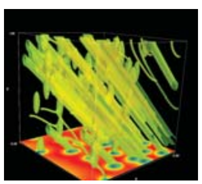
Numerical simulation of realistic pinning centers
Prediction of optimal defect concentration for largest critical current

MoGe slap with parallel current and field shows reentrance.
Questions:
- ➢ Reason & underlying mechanism for this effect?
- ➢ What are the conditions for the appearance of this effect?

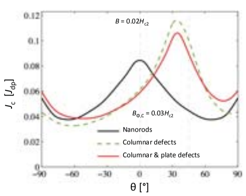


Numerical simulation of realistic geometries; Prediction of optimal defect concentration for largest reentrance effect

① Nanorods + Columns



Nanorods & Irradiated columnar defects

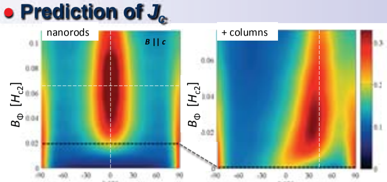


Simulation results for the angular dependence of the critical current for a single defect concentration

- **The effects from different defects are not additive.**
- **The alignment of the dominant inclusions define peaks.**
- **The peak at α = 0° decreases.**

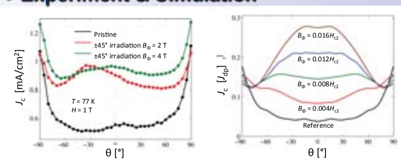
→ ***Close to quantitative agreement of experimental results and explanation of the underlying mesoscopic mechanisms***

Prediction of J_c



② Columns at ±45°

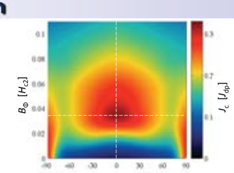
Experiment & Simulation



Left: Experimental $J_c(\alpha)$ dependence. *Right:* Numerical $J_c(\alpha)$ dependence for different defect concentrations.

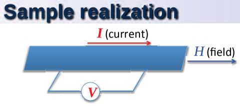
- ➢ Sample is realized as a cuboid, discretized using a regular mesh of 128x512x768 grid points with mesh size of $\xi_0/2$
- ➢ (quasi-)periodic boundary conditions
- ➢ Inclusions and irradiation tracks: low-T_c component regions
- ➢ Anisotropy in c-direction: anisotropy factor γ=5
- ➢ For each field and pinning configuration an IV curve is calculated from which the critical current is obtained

Prediction



③ Parallel fields

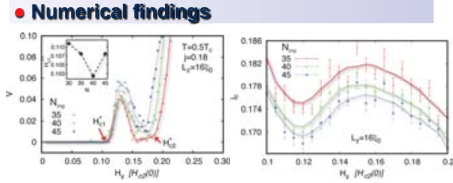
Sample realization



Sample parameters
ξ_0=6-8 nm
λ=400nm
T_c~6.15 K
thickness=100nm~16ξ_0

- ➢ Sample is discretized using a regular mesh of 512x128x32 grid points with mesh size of $\xi_0/2$ → realistic thickness
- ➢ 0-100 spherical inclusions (low-T_c) with diameter 5ξ_0 randomly placed → average over different disorder realizations
- ➢ A fixed constant current applied in y-direction as the variable magnetic field

Numerical findings



Left: As function of defect concentration: Resistance vs. magnetic field (inset: lowest H_{c1}). *Right:* J_c dependence on field.

New discovery: a new periodically "rotating" vortex state appears at intermediate field strength having finite resistance

Conclusion & References

- ✓ Large-scale parallel TDGL integration methods allow to make the study of mesoscopic systems including the collective behavior
- ✓ Experiments verify simulation results
- ✓ Effects from different types of inclusions are strongly non-additive
- ✓ Analysis of experimental results with numerical simulations allows prediction of new types of materials with higher critical current: ***Critical current by design***
- ✓ Advanced vortex detection & tracking help to understand the underlying mechanism → **Discovery of new effects**

Related References:

[1] V. K. Vlasko-Vlasov, A. Glatz, A. E. Koshelev, U. Welp, and W. K. Kwok
Anisotropic superconductors in tilted magnetic fields
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[2] V. Vlasko-Vlasov, A. Koshelev, A. Glatz, C. Phillips, U. Welp, and W. Kwok
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[3] Ivan A. Sadovskyy, et. al.
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[4] Y. L. Wang, A. Glatz, G. Kimmel, I. S. Aranson, L. R. Thoutam, Z. L. Xiao, G. R. Berdiyorov, F. M. Peeters, G. W. Crabtree & W. K. Kwok
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