Irradiation Effects of Vortex Pinning in High Performance High Temperature Superconductors

Wai –K. Kwok*,1, K. Kihlstrom1,3, M. LeRoux1, B. Shen1, L. Fang1, Y. Jia1, V. Mishra1, A. E. Koshelev1, D. M. Miller1, U Welp1, I. Sadovsky1, A. Glatz1, S. Zhu1, J. M. Zuo2, G. W. Crabtree1,3, A. Kayani4, H. –H. Wen5, J. Karpinski6, L. Civale7, M. Rupich8, S. Fleshler8, A. Malozemoff8, V. Selvamanickam9,10

1Argonne National Laboratory, Argonne, IL 60439 USA, 2Dept. of Physics, University of Illinois-Urbana Champaign, Urbana IL 61801 USA, 3Dept. of Physics, University of Illinois at Chicago, Chicago, IL 60607 USA, 4Dept. of Physics, Western Michigan University, Kalamazoo, MI 49008 USA, 5Dept. of Physics, Nanjing University, Nanjing 210093 China, 6Institute of Condensed Matter Physics EPFL, CH-1015 Lausanne, Switzerland, 7Los Alamos National Laboratory, Los Alamos, NM 87545 USA, 8American Superconductor Corporation, USA, 9SuperPower Inc., USA, 10University of Houston, Houston, TX 77204, USA

Vortex behavior in high temperature superconductors is responsible for the entire spectrum of electromagnetic response. A high priority is placed on understanding the vortex pinning mechanism from its nanoscale electronic interactions at the level of the vortex core to the ensuing macroscopic critical current performance. I will present our latest work on using particle irradiation to enhance the current carrying capacity of commercial YBCO coated-conductors and iron-based superconductors. For the former, we demonstrate the near doubling of the critical current in the temperature and field range targeted for superconducting rotating machinery. For the latter, we demonstrate the potentially high critical currents that can be achieved in these new superconductors. In addition, by combining proton and heavy-ion irradiation induced defects with the inherent pinning landscape of these high-temperature superconducting materials, we show that such ‘mixed-pinning’ landscape can dramatically increase the critical current, especially at high magnetic fields. Finally, I will discuss the potential for achieving Critical Current by Design – that is, realizing a quantitative correlation between the observed critical current density and mesoscale mixed pinning landscapes by using realistic input parameters in an innovative and powerful large-scale time dependent Ginzburg-Landau approach to simulating vortex dynamics.

This work was supported by the Center for Emergent Superconductivity, an Energy Frontier Research Center funded by the US Department of Energy, Office of Science, Office of Basic Energy Sciences.

a-3 Physics and Chemistry: Vortex physics
Intrinsic pinning in Fe- and Cu-based superconductors

Boris Maiorov*
Condensed Matter & Magnet Science, Los Alamos National Laboratory, Los Alamos, NM 87544

Besides strong thermal fluctuations due to the small coherence length and relatively high critical temperature, vortex matter in Fe and Cu-based superconductors share other characteristics such as their layered structure. These in turn have important consequences in determining how vortices are trapped by different pinning potentials. Angular dependent critical current measurements are extremely useful to determine in which way vortices are trapped and how effective different pinning centers are. It is also important to extract all the information available about vortex dynamic from non-linear transport experiment; namely analyze the power-law dependence often found between electric field and applied current. The exponent N, gives important microscopic information about the depinning processes that vortices undergo.

A common feature among iron and cuprate high temperature superconductors is the layered structure; consisting of intercalated conducting and insulating planes. This intrinsic layering gives rise to the electronic mass anisotropy as well as a periodic planar pinning potential. Depending on the insulating layer size the anisotropy of the compound can vary from close to 1 up to hundreds for Bismuth- or Mercury-based superconductors. The effect on vortices, also known as *intrinsic-pinning*, of these periodic planar potentials should not depend on the specifics of different materials but rather be universal. In this talk I will show transport measurements, consistent of critical current and N values, of the different angular regimes of the vortex dynamics that confirm the generality of the intrinsic pinning found in YBCO films as well as in iron based superconductors.

We will explore theoretical description of these angular regimes, both in the 3D vortex regime where vortices are considered as continuous lines, as well as in the 2D regime where vortices along the ab-planes are considered to be pancake like.

![Figure 1. Angular dependence of N values at $\mu_0 H = 9$T, and different temperatures measured in thin films of (a) YBa$_2$Cu$_3$O$_7$ and (b) SmFeAsO$_1$-$xF_x$.](image)

Acknowledgment: Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering
Critical Current Densities in Pristine and Irradiated (Sr,K)Fe$_2$As$_2$ Single Crystals

T. Tamegai*,1, T. Taen1, F. Ohtake1, S. Pyon1, H. Kitamura2
(1Department of Applied Physics, The University of Tokyo, 2NIRS)

Since the discovery of iron-based superconductors, great attention is focused on this new class of materials from both fundamental and applied aspects. Compared with widely studied Ba(Fe,Co)$_2$As$_2$, alkali metal substituted 122 compounds are more difficult to grow, and the understanding of their physical properties are still under way. However, recent high-quality single crystals of (Ba,K)Fe$_2$As$_2$ allows us to clarify their fundamental properties including the vortex physics. In addition, performance of powder-in-tube (PIT) wires of (Ba,K)Fe$_2$As$_2$ is steadily improving and self-field $J_c$ at 4.2 K has exceeded 1x10$^6$ A/cm$^2$ [1]. On the other hand, extensive studies on (Sr,K)Fe$_2$As$_2$ have not yet been undertaken. Very recently, similar PIT wires have been fabricated and good $J_c$ performance is demonstrated [2]. With these situations in mind, we studied the physical properties of high-quality (Sr,K)Fe$_2$As$_2$ single crystals.

Single crystals of optimally-doped (Sr,K)Fe$_2$As$_2$ have been grown using flux method as described in Ref. [3]. Unlike the case of (Ba,K)Fe$_2$As$_2$, all the crystals do not show sharp superconducting transitions. Still, we can select a good piece of single crystals with $T_c \sim 37$ K with $\Delta T_c \sim 0.3$ K determined from the diamagnetic transition. The critical current density ($J_c$) evaluated from the irreversible magnetization reaches 2x10$^6$ A/cm$^2$ at 2 K under self-field, which is comparable to that in (Ba,K)Fe$_2$As$_2$. However, after the introduction of artificial defects using 3 MeV proton and 800 MeV Xe irradiation, $J_c$ is enhanced only up to 7x10$^6$ A/cm$^2$ at 2 K under self-field, which is smaller than that in (Ba,K)Fe$_2$As$_2$. In the pristine sample, $J_c$ decreases rapidly at high temperatures, but becomes larger than that in (Ba,K)Fe$_2$As$_2$. In addition, the field dependence of $J_c$ at high temperatures is weaker than that in (Ba,K)Fe$_2$As$_2$. These facts suggest that the intrinsic disorder is stronger in (Sr,K)Fe$_2$As$_2$ than in (Ba,K)Fe$_2$As$_2$.

Extended Molecular Dynamics Methods for Vortex Dynamics in Nano-structured Superconductors

Masaru Kato*,1, Osamu Sato2

(1Osaka Prefecture University, 2Osaka Prefecture University College of Technology)

For applications of superconductors, vortex dynamics is a key feature, because when vortices move, the zero resistivity of a superconductor is destroyed. In order to investigate the dynamics of vortices theoretically, we use phenomenological time-dependent Ginzburg-Landau equations [1] or the molecular dynamics method. Especially, the molecular dynamics method is effective when we consider many vortices [2]. However, in this method, several features are missing, when we consider real superconducting systems. For example, when vortices move, heat generation occurs. If the vortex motion is uniform, this heat generation is also uniform. But when vortex motion is not uniform, such as in a corbino disk [3], non-uniform heat generation occurs and then non-uniform temperature distribution appears. A vortex has a transport-entropy, and then motion of the vortex is affected by this temperature distribution. In order to incorporate such effect, we must solve the heat transport equation with the molecular dynamics equation for vortices. Another feature is a retardation effect, which comes from quasi-particle recombination after fast movement of vortices [4]. After a vortex moves, the order parameter that was inside of the vortex core is restored to the uniform value, but it takes a time for recombining Cooper pairs. Then, if vortices move fast, the vortex motion is affected by a preceding vortex. In order to incorporate such retarded effect, we introduce a condensation energy field, which is proportional to the square of the absolute value of the order parameter.

Then we solve following equations,

$$\eta \frac{d\mathbf{v}_i}{dt} = f_{\text{di}} + f_{\text{vi}} + f_{\text{pi}} + f_{\text{ri}} + f_{\text{fi}} + f_{\text{R}}.$$

Here, $\mathbf{v}_i$ is a velocity of i-th vortex, and $f_{\text{di}}$, $f_{\text{vi}}$, $f_{\text{pi}}$, $f_{\text{ri}}$, and $f_{\text{R}}$, are a driving force from an external current, a vortex-vortex interaction from other vortices, a pinning force from impurities, a force from a screening current and an external field and a thermal fluctuation force, respectively. $f_{\text{f}} = -S_\phi \text{grad} T$ is an entropy force from the temperature distribution. $f_{\text{R}} = -\text{grad} V_{\text{cond}}(r)|_{r=r_i}$ is a force from the condensation energy distribution.

We solve these equations and investigate the vortex dynamics, especially structures of dynamical vortex lattices. In Fig. 1, we show a typical vortex configuration in a corbino disk.

Unusual $I$-$V$ Relation for Rotating Vortices in 

a Corbino Disk

Y. Kawamura*1, Y. Matsumura1, Y. Yamazaki1, S. Kaneko1, N. Kokubo2, 
S. Okuma1

(1Department of Physics, Tokyo Institute of Technology, 
2University of Electro-Communications)

We have studied the dynamic response of the vortex lattice driven by a radial current in amorphous Mo$_x$Ge$_{1-x}$ films with a Corbino geometry. The vortices are rotated around the center of the sample by the frustrated Lorentz force inversely proportional to the radius. We have observed either the liquid-like or the lattice-ring rotation in which the vortices or the rings near the center rotate faster [1]. This is in contrast to the results for YBCO single crystals where the rigid-disk-like rotation was clearly observed [2]. We have detected the rotating rings composed of triangular vortex arrays from a mode-locking resonance, where dc current-voltage ($I$-$V$) characteristics superimposed with ac current $I_{rf}$ are measured. For ordinary strip samples, when $I_{rf}$ is increased from zero, the $I$-$V$ curves shift upward. This is due to the reduced pinning effect by increased $I_{rf}$. In the Corbino geometry studied here, however, we observe an unusual response: $V(I)$ at high $I$ shows a trend to decrease with increasing $I_{rf}$. We propose a picture that accounts for the unusual behavior.