Toward Superconducting Critical Current by Design

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The interaction of vortex matter with defects in applied superconductors directly determines their current carrying capacity. Defects range from chemically grown nanostructures and crystalline imperfections to the layered structure of the material itself. The vortex-defect interactions are nonadditive in general, leading to complex dynamic behavior that has proven difficult to capture in analytical models. With recent progress in advanced computing, a new paradigm has emerged that aims at simulation-assisted design of defect structures with predictable powers. This concept of critical-current-by-design aims at predicting the optimal defect landscape for targeted applications by elucidating the vortex dynamics responsible for the bulk critical current. To highlight this approach, we demonstrate the synergistic combination of critical current measurements on commercial high-temperature superconductors containing self-assembled and irradiation-tailored correlated defects with large-scale time-dependent Ginzburg–Landau numerical simulations of vortex dynamics. The qualitative agreement between experiments and simulations allows making numerical predictions for a wider parameter range and hence opens the route to the critical-current-by-design paradigm.

Superconducting vortices appear inside superconductors in the presence of sufficiently large magnetic fields and are responsible for the entire electromagnetic behavior of applied superconducting materials. In particular, the onset of vortex motion limits the highest dissipation-less electrical current—the critical current—the superconductor can carry. At the microscopic level, vortices can be viewed as nonsuperconducting cores that are surrounded by circulating persistent superconducting currents. The radius of the core is approximately given by the superconducting coherence length, \( \xi \), which for high-temperature superconductors is of the order of 1.5–3 nm, and the circulating supercurrents extend out to the magnetic penetration depth, \( \lambda \), which is of the order of 100–200 nm. When an external electric current is passed through the superconductor, the vortices experience the Lorentz force, which sets them in motion, resulting in a voltage drop across the superconductor and hence dissipation: the superconductor loses its superconducting properties. A variety of defects in the superconducting material (precipitates, point defects, grain boundaries, dislocations, stacking faults, strain fields, etc.) can induce spatial variations of the superconducting state that serve to pin the normal vortex cores and prevent their motion. Thus, an important goal of materials science of applied superconductors is the design and synthesis of the most effective vortex pinning microstructures that results in the largest critical current. Although a tremendous amount of knowledge, systematics and practical experience has been gained in this pursuit, see for instance reviews, the fundamental solution to the dynamics of interacting elastic vortex lines in a disordered medium is still an

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open problem. The technical challenge consists in the accurate statistical summation of individual vortex–vortex interactions and pinning forces\cite{27} which is akin to a many-body problem with long-range interactions. For example, the critical currents may be estimated based on energy and force balance considerations, see, e.g., reviews\cite{8–10} only for the most simple cases, such as uniformly distributed weak pinning centers. These estimates, however, do not describe the more practically important cases of multiple large-size defects occupying a considerable fraction of the material, as in most commercial high temperature superconductors. In such cases, the vortex pinning effects of different pinning sites are not simply additive, especially for high concentration of defects and in the presence of strong magnetic fields. In general, critical currents for such complicated defect structures can only be computed using large-scale numerical modeling.

The rapid progress of high performance computing combined with sophisticated numerical methods and materials synthesis provides a strong impetus to realize approaches with predictive power. A new area driven by this powerful combination is the materials genome initiative\cite{11,12} that aims at predicting their properties. A new area driven by this powerful combination is the materials genome initiative\cite{11,12} that aims at predicting their properties. A new area driven by this powerful combination is the materials genome initiative\cite{11,12} that aims at predicting their properties. A new area driven by this powerful combination is the materials genome initiative\cite{11,12} that aims at predicting their properties. A new area driven by this powerful combination is the materials genome initiative\cite{11,12} that aims at predicting their properties.

A well-established description of superconducting properties is based on the phenomenological time-dependent Ginzburg–Landau (TDGL) model\cite{13,14}. In this model, the superconducting state is represented by a complex-valued superconducting order parameter $\psi$ which is modeled through the spatial dependence of the critical temperature $T_c$ and pin sites, for vortex-line elasticity, vortex cutting and reconnection, in other words, all the interactions that are relevant for describing pinning. The TDGL model can be reduced to a nonlinear partial differential equation for the order parameter, given here in dimensionless form:

$$
(\partial + i\mu)\psi = \xi(T)\psi - |\psi|^2\psi + (V - iA)\cdot\nabla\psi + \zeta(r,t) \tag{1}
$$

We use the temperature-dependent coherence length $\xi = \xi(T)$ as unit of length, which allows to account for the temperature dependence of physical quantities in a computationally efficient way. The micro and nanostructure of the superconductor is modeled through the spatial dependence of the critical temperature $T_c(r)$ contained in the prefactor of the linear term, $\xi(r)$. This prefactor is $\xi(r) = 1$ in the superconductor and is negative, $\xi(r) < 0$, in the nonsuperconducting defect (see Supporting Information for details). $A$ is the vector potential describing the magnetic field, $\mu$ is the electrostatic potential, and $\zeta(r,t)$ is the temperature-dependent Langevin noise. We employed the so-called infinite-$\lambda$ approximation within which the vector potential is fixed by the applied magnetic field. This approximation is suitable for type-II superconductors with high Ginzburg–Landau parameter ($\lambda/\xi = 100$ for the experimental system) at high magnetic fields, when the intervortex distance is much smaller than the London penetration depth $\lambda$ and small spatial variations of the magnetic field can be neglected.

For realistic pinning microstructures, Equation (1) can be solved only numerically. This task proves to be computationally very demanding, and thus far, mostly mesoscopic or 2D systems have been analyzed with this method, see, e.g., refs.\cite{15–18} Recently, we have developed a stable implicit iterative solver for TDGL equation\cite{19} based on the Jacobi method. This solver running on high-performance general-purpose graphic processor units allows to simulate 3D samples large enough that finite size and surface effects become negligible.\cite{20,21} Predictions for macroscopic quantities such as the critical current are now possible, thereby enabling the concept of critical-current-by-design. We demonstrate this concept on technologically important rare earth barium copper oxide (REBa$_2$Cu$_3$O$_{y+\delta}$ or REBCO) coated conductors and validate the results on samples with clearly identifiable pinning effects due to linear correlated defects in the form of self-assembled barium zirconate (BZO) nanorods and irradiation tracks introduced by heavy-ion irradiation.

We present results on two sets of commercially available REBCO-coated conductors, one containing self-assembled BZO nanorods, the other without. The samples were grown on Hastelloy substrates using metal–organic chemical-vapor deposition (MOCVD). The in-plane texture of a MgO buffer layer located between the superconductor and the substrate is achieved with an ion-beam-assisted deposition (IBAD) process.\cite{22} It has recently been shown that the addition of BZO can lead to the formation of self-assembled BZO nanorods inside the REBCO matrix during the synthesis of the superconductor.\cite{23–26} The nanorods grow largely along the c-axis of REBCO with typical diameters of ~5–10 nm and lengths of several hundreds of nanometers that is mostly limited by planar precipitates and stacking faults. Their addition results in substantial increases of the critical current density with $J_c$, values reaching ~8 MA cm$^{-2}$ at 30 K and in a field of 9 T applied parallel to the c-axis.\cite{27} At high temperatures ($T \approx 60$ K), the linear shape of the BZO nanorods is responsible for the pronounced peak in the field-angle dependence of $J_c$ for applied fields aligned with the c-axis, whereas at lower temperatures, strain fields associated with the BZO nanorods and/or nanoparticles induce almost isotropic $J_c$-enhancements.\cite{27,28}

An alternative approach to introducing linear defects is realized by irradiation with high-energy heavy ions.\cite{29} For certain ranges of parameters—such as weight and energy of the ions, thermal and electric conductivity of the target material, and rate of energy transfer—continuous amorphous tracks are formed in the target material. Typical track diameters fall in the range of 5–10 nm.\cite{29–31} These heavy-ion-induced columnar defects are known to be the most effective vortex pinning centers for applied fields aligned with the tracks due to their ideal size for confining vortices, and their pinning effects have been extensively studied.\cite{12–14} In contrast to self-assembled BZO nanorods that are chemically inserted, irradiation-induced columnar defects can be introduced at arbitrary angles and over a wide range of areal density,\cite{35–38} allowing for a convenient means of
investigating the constructive or destructive pinning action of several types of coexisting pinning sites.

In this work, we present (i) a study of vortex pinning in a REBCO-coated conductor with self-assembled BZO nanorods before and after heavy-ion irradiation at 45° and (ii) a study of the cumulative effect of splayed heavy ion irradiation at angles of +45° and −45° to the c-axis in a REBCO-coated conductor without nanorods. In both studies, we compare experimental and numerical results and demonstrate the validity of our numerical TDGL approach. Subsequently we explore a wider parameter range with numerical simulations to determine optimal pinning configurations.

Figure 1 summarizes our results on a REBCO-coated conductor containing BZO nanorods into which columnar-shaped tracks have been introduced at an angle close to 45° from the c-axis. The nanorods are oriented along the c-axis, and the dark striations are Moiré-patterns resulting from the imaging setup. In panels (a–c) the color scheme was chosen to enhance the contrast. d) Angular dependence of the critical current $J_c(\theta)$ before and after irradiation in REBCO-coated conductor samples at a temperature of 77 K and in a magnetic field of $B = 1$ T. The sample was irradiated with 1.4 GeV Pb$^{56}$ ions at 45° from the c-axis. In the unirradiated sample, the presence of BZO nanorods induces a large peak when the field is applied parallel to the c-axis of the REBCO layer, and a small peak is also present for the ab-plane due to intrinsic pinning, RE$_2$O$_3$ nanoplates, and stacking faults. In the irradiated sample, the peak has shifted toward the direction of irradiation. e) Representative configuration of vortices and defects in the simulation. A snapshot of the isosurfaces of the order parameter is shown in red. The vortices follow the direction of the magnetic field applied along the c-axis. Columnar defects and nanorods (displayed shorter than actually used in the simulations for illustration purposes) are shown in gray. f) Angular dependence of the critical current from simulations, normalized to the depairing current. Reference simulation with sample containing nanorods along the c-axis is shown in black. The addition of columnar defects at 45° from the c-axis shifts the peak as shown by the green dotted line. The addition of plate-like defects in the ab-plane modifies the angular dependence as shown in red.
shows a comparison of the angular dependence of \( J_c \) from transport measurements in unirradiated (black) and irradiated at 45° (red) samples with self-assembled BZO nanorods. In these measurements, the current flows along the ab-plane and is always perpendicular to the applied magnetic field. The field is rotated from the c-axis (\( \theta = 0° \)) to the ab-plane (\( \theta = 90° \)). The irradiation-induced columnar tracks are oriented in such a way that they are perpendicular to the current flow.

The angular dependence of the critical current \( J_c(\theta) \) conveniently characterizes the nature of the dominant correlated pinning centers. Pinning contributions from the inherent layered structure of the material, from in-plane nanoplates and from stacking faults create two strong peaks in \( J_c \) for fields oriented along the ab-plane, at \( \pm90° \). As expected, the sample with BZO nanorods presents a pronounced peak in \( J_c \) near \( B||c \)\[23,26,39\] but at the expense of the in-plane critical current \( J_c(0°) \). As a result, at 77 K and \( B = 1 \) T, the BZO nanorods actually reverse the critical-current anisotropy from 2 to 0.5, defined as \( J_c(0°)/J_c(45°) \) as can be seen by comparing the data labeled “pristine” in Figure 3d and the data labeled “nanorods” in Figure 1d.

Remarkably, in the sample containing both BZO nanorods and irradiation-induced columnar defects, we observe only a single peak in the critical current at \( \theta = 45° \), instead of the superposition of a \( J_c \)-peak due to the BZO nanorods at \( \theta = 0° \) and a \( J_c \)-peak due to the columnar defects at \( \theta = 45° \). Namely, the vortex pinning due to the BZO nanorods has been strongly suppressed by the introduction of the irradiation tracks. Such an effect is a clear example of the nonadditive nature of two types of pinning centers.

When describing this situation theoretically, we mainly focus on the two types of pinning centers that dominate the angular dependence of the critical current and of which we have quantitative knowledge: nanorods and irradiation induced columnar defects. Furthermore, we model intrinsic pinning by means of the Lawrence–Doniach model\[42\] and a modified Laplacian describing anisotropy. In addition, we consider contributions from in-plane plate-like defects. The model of the tape nanostructure, that includes both the BZO nanorods aligned along the c-axis and the columnar defects inclined at \( \theta = 45° \), is presented in Figure 1e.

Our simulation allows for an unprecedented insight into the 3D vortex dynamics as shown in the videos in the Supporting Information. We find that for large enough concentrations of irradiation-induced columnar defects, vortices aligned with the BZO nanorods can easily jump from one nanorod to the next by sliding along the oblique columnar defects. This effect is directly responsible for the reduced critical current for magnetic field along the BZO nanorod direction. The resulting simulated angular dependences of \( J_c \) are shown in Figure 1f and are in good qualitative agreement with the experiment. In particular, they depict the nonadditive effect of the two types of pinning centers and that the pinning action of the BZO nanorods is no longer visible. We therefore attribute the loss of pinning by the nanorods at \( \theta = 0° \) observed in the experiment to a “vortex sliding” effect between nanorods induced by the oblique continuous columnar tracks, see insets in Figure 2. In other words, the columnar defects tilted at 45° effectively reduce the nucleation energy of local vortex kink formation and thus, help vortices to slide from one nanorod to the next one.

We typically observe that dominant extended defects define the critical current peak of \( J_c(\theta) \) at their tilt angle, while all other defects only slightly modify the shape of \( J_c(\theta) \), without adding additional peaks. For example, coated conductor samples contain a fair amount of stacking faults and ab-plane precipitates that disrupt the columnar defects and the BZO nanorods. To elucidate their role, we simulate the system with and without in-plane, plate-like defects. The predominant effect of these planar

![Figure 2](https://www.advancedsciencenews.com/toc/advmat/1600521/fullsize.jpg)

**Figure 2.** a) Angular dependence of the critical current (normalized to the depairing current \( J_{\text{dp}} \)) for different concentrations of nanorods in a magnetic field of 0.02\( \mu \)T. One can see the prominent peak along the c-axis (\( \theta = 0° \)) for a wide range of nanorod concentration (expressed in matching field \( B_{\text{m}} \)) ranging from \( B_{\text{m}} = 0.025\) to \( 0.1 \)\( \mu \)T. This corresponds to the volume fraction of 5%–20% occupied by nanorods inclusions. The peak critical current at \( \theta = 0° \) and \( B_{\text{m}} = 0.07\)\( \mu \)T is \( J_{\text{c}} = 0.14\)\( \mu \)A. The white dotted curve shows the optimal concentration of nanorods for maximum critical current at a given angle of applied field. Inset: Sketch of the vortex pinned by a nanorod for \( B||c \). b) Angular dependence of the critical current for different concentration of columnar defects \( B_{\text{m}} \) tilted at \( \theta = 45° \) and at a fixed concentration of nanorods (with matching field \( B_{\text{m}} = 0.02\)\( \mu \)T shown by dashed line in panel (a). With increasing concentration of columnar defects, the peak shifts from \( \theta = 0° \) to \( 45° \). The near-optimal critical current corresponds to the angular range \( \theta = 30°–40° \) and concentration of columnar defects \( B_{\text{m}} = 0.02–0.04\)\( \mu \)T (or volume fraction of 6%–11% occupied by them). Inset: Vortex sliding on tilted columnar defects.
defects is an enhancement of the critical current for in-plane magnetic fields, $\theta = 90^\circ$. Comparing the dashed green and the red lines in Figure 1f, one sees that the in-plane defects slightly reduce the peak in fields aligned with the columnar defects, $\theta \approx 45^\circ$.

Additionally, to obtain predictive results, we numerically analyze a wide range of concentrations of BZO nanorods and columnar defects. In Figure 2, we show density plots of the simulated critical current as a function of angle $\theta$ and concentration of the defects characterized by the matching field $B_\Phi$. Figure 2a shows that with increasing nanorod concentration (without columnar defects) a prominent maximum in $J_c(\theta)$ emerges around $\theta = 0^\circ$. For nanorod concentrations ranging from $B_{\Phi,N} \approx 0.025H_{c2}$ to $\approx 0.1H_{c2}$, the height and angular width of this maximum are predicted to be almost independent of concentration. With further increase of the nanorod concentration, the $J_c$ peak at $\theta = 0^\circ$ decreases.

Figure 2a also shows that the two $J_c$ peaks at $\theta = \pm 90^\circ$ attributed to intrinsic pinning from the material’s layered structure are suppressed when the nanorod defect density exceeds $B_{\Phi,C} \approx 0.04H_{c2}$. The critical current for $B||c$ approaches its maximum at $B_{\Phi,N} \approx 0.07H_{c2}$, which corresponds to a volume fraction of 14% occupied by nanorods. We find that the mechanism of this suppression is the same as described above for vortices jumping between nanorods by “sliding” through the columnar defects, but this time it is the nanorods that create “bridges” on which vortices can move from one intrinsic layer to the next. Experimentally, we note that the critical current for $B||ab$ due to intrinsic pinning above an overall isotropic baseline level indeed decreases with increasing concentration of BZO nanorods, in agreement with our simulations. This trend holds even though the baseline $J_c$ and additional pinning from planar precipitates—both not included in the current simulations—varies significantly between samples.

Figure 2b shows the effect of increasing the concentration of irradiation-induced columnar defects for a fixed concentration of BZO nanorods of $B_{\Phi,N} \approx 0.02H_{c2}$. The intrinsic pinning peaks at $\pm 90^\circ$ vanish above a dose-matching field of $B_{\Phi,C} \approx 0.06H_{c2}$. A similar reduction of intrinsic pinning was observed experimentally in YBCO films that contain inclined columnar defects.\cite{43} Furthermore, the peak at $\theta = 0^\circ$ due to the BZO nanorods rapidly shifts to $\approx 45^\circ$ with increasing columnar defect concentration from $B_{\Phi,C} = 0.02H_{c2}$ to $0.04H_{c2}$. For even larger columnar defect concentrations, this latter peak becomes smaller as the effective barrier for vortex hopping between neighboring columnar defects decreases. This shift in the $J_c$ peak when BZO nanorods compete with columnar defects oriented at a different angle clearly highlights the complex vortex dynamics in a mixed pinning environment. Although newly added defects can pin vortices, they may also facilitate vortex hopping or sliding between neighboring preexisting defects under specific conditions. Hence the effect of these defects on vortices can be tailored by controlling the concentrations and mutual orientations of the defects.

Nonadditive effects can also occur between two identical types of pinning centers. For instance, irradiation-induced columnar defects oriented at $\pm 45^\circ$, also known as splayed irradiation, may offer a route toward a marked reduction of the anisotropy of $J_c$ at an overall high value in single crystals and thin films.\cite{44} The REBCO sample without BZO nanorods was irradiated with 1.4 GeV $^{208}$Pb ions at both $-45^\circ$ and $+45^\circ$ from the crystalline $c$-axis with a total dose of $B_{\Phi,X} = 2$ T ($B_{\Phi,C} = 1$ T in each direction). As expected, the Pb-ion irradiation generates perpendicular crosed damage tracks at $\pm 45^\circ$ from the $c$-axis. The morphologies of the crossed columnar defects are presented in the Z-contrast scanning transmission electron microscopy images of Figure 3a–c. Similar to the REBCO films reported earlier,\cite{40} these films also contain a large number of correlated nanoplates and stacking faults parallel to the film plane. We apply the current along the $ab$-plane perpendicular to the splay and applied magnetic field. The changes induced by the crossed columnar defects on the angular dependence of $J_c$ are shown in Figure 3d. We find that $J_c$ is enhanced over a wide angular range. For the irradiated sample, the increase of $J_c$ reaches 27% for $B||ab$ and 71% for $B||c$. As a result, the critical-current anisotropy is markedly reduced down to 1.17 when defined as $J_c(B||ab)/J_c(B||c)$, or 1.3 when more properly defined as $\max(J_c)/\min(J_c)$.

We carried out TDGL simulations of the vortex dynamics in REBCO containing splayed columnar defects. Figure 3e shows a representative snapshot of the arrangement of vortices and defects. The results of the simulation for different concentrations of crossed columnar defects are shown in Figure 3f. The simulation qualitatively reproduces the reduction of the anisotropy and the overall increase of the critical current observed experimentally in Figure 3d. At low concentration of splayed defects ($B_{\Phi,X} = 0.008H_{c2}$), the simulation of the angular dependence of $J_c$ reveals two maxima located at $\pm 45^\circ$ as might be expected for a simple addition of pinning effects. However, with increasing concentration the two maxima merge to form a single flat maximum around $\theta = 0^\circ$, as in the experiment. Thus our simulations suggest that a fairly isotropic $J_c$ can be achieved for relatively low defect concentration with a rather modest increase in $J_c$, whereas the maximum enhancement of $J_c(B||c)$ occurs at significantly higher defect concentration accompanied by a sizable reverse anisotropy, i.e., $J_c(B||c) > J_c(B||ab)$.

Figure 4 shows the simulated plot of $J_c$ for different concentrations of splayed defects and angles of applied field. Again, as in Figure 2, one can observe two peaks at $\theta = \pm 90^\circ$ due to intrinsic pinning. The combination of columnar defects tilted at $\pm 45^\circ$ results in a broader peak near $\theta = 0^\circ$ compared to the peak in the angular dependence of Figure 2a for nanorods. The maximum of the critical current occurs at a matching field of $B_{\Phi,X} = 0.035H_{c2}$, corresponding to a volume fraction of 9.3%.

The optimal concentration of nanorods predicted for a REBCO conductor (Figure 2a) is approximately three to four times larger than the values observed in our experiments on currently available industrial samples containing 7.5 mol% Zr. Extensive recent work on research-scale samples has shown that the critical current density increases strongly with Zr-content, that is, with the concentration of nanorods,\cite{27,19,45–48} and samples with Zr-doping up to 25 mol% have been synthesized. Our simulations (Figure 2a) are aligned with these studies and suggest that there is still room for further enhancement. In contrast, the predicted optimal concentration of irradiation-induced splayed tracks in a pristine sample (Figure 4) corresponds
closely to the concentration used in our experiments, and no further improvement is expected. However, we expect that the addition of splayed columnar defects will decrease the critical-current anisotropy of the sample.

Our large-scale TDGL simulations describing the joint action of different dominant pinning centers provide valuable insights for the design of effective mixed pinning landscapes by elucidating the vortex dynamics responsible for the enhancement of $J_c$ in commercial high temperature superconductors. Visualizing the real dynamics is difficult, as few, if any, experimental techniques can resolve both the microscopic magnetic structure and short timescale. It is however key to achieving higher and more isotropic critical currents in these high temperature superconductors.

In summary, we introduced the new critical-current-by-design paradigm. This paradigm aims at predicting the optimal pinning landscapes for maximum critical current in targeted high-temperature superconducting applications.

We illustrated this concept on technologically important rare earth barium copper oxide coated conductors and validated the results on samples with clearly identifiable pinning effects due to linear correlated defects in the form of self-assembled barium zirconate nanorods and irradiation tracks introduced by heavy-ion irradiation. The TDGL simulations elucidate the vortex dynamics responsible for the non-additive behavior of the vortex-defect interaction in the presence of different types of correlated defects with various spatial orientations. In particular, we observed a vortex-sliding scenario, directly demonstrating the dynamics that can result from synergies between different types of pinning. Using this approach, we also can predict the optimal concentrations of these defects for maximal critical current. As characterization and models of realistic pinning centers improve, and as computational performance increases, the quantitative prediction of a superconductor’s critical current from its microstructure now seems within reach.
The dotted curve corresponds to the optimal volume fraction of 9.3% occupied by columnar inclusions. The white

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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[1] A. M. Campbell, J. E. Evetts, Adv. Phys. 1972, 21, 199.
[2] E. J. Kramer, J. Appl. Phys. 1973, 44, 1360.
[3] D. Dew-Hughes, Phil. Mag. 1974, 30, 293.
[4] P. Kes, in Concise Encyclopedia of Magnetic & Superconducting Materials, (Ed: J. Evetts), Pergamon Press, Oxford 1992, p. 163.
[5] R. M. Scanlan, A. P. Malozemoff, D. C. Larbalestier, Proc. IEEE 2004, 92, 1639.
[6] A. Godake, B. ten Haken, H. H. J. ten Kate, D. C. Larbalestier, Supercond. Sci. Technol. 2006, 19, R100.
[7] A. I. Larkin, Yu. N. Ovchinnikov, J. Low Temp. Phys. 1979, 34, 409.
[8] G. Blatter, M. V. Feigel’man, V. B. Geshkenbein, A. I. Larkin, V. M. Vinokur, Rev. Mod. Phys. 1994, 66, 1125.
[9] G. Blatter, V. B. Geshkenbein, in Conventional and High-T_c, Superconductors, Vol 1, (Eds: K. Bennemann, J. Ketterson), Springer, Berlin 2003, p. 726.
[10] E. H. Brandt, Rep.Prog. Phys. 1995, 58, 1465.
[11] S. Curtarolo, G. L. W. Hart, M. B. Nardelli, N. Mingo, S. Sanvito, O. Levy, Nat. Mater. 2013, 12, 191.
[12] Materials Genome Initiative, https://www.whitehouse.gov/mgi, (accessed: December 2014).
[13] A. Schmid, Phys. Kondens. Materie 1966, 5, 302.
[14] I. S. Aranson, L. Kramer, Rev. Mod. Phys. 2002, 74, 99.
[15] V. A. Schweigert, F. M. Peeters, P. S. Deo, Phys. Rev. Lett. 1998, 81, 2783.
[16] G. W. Crabtree, D. O. Gunter, H. G. Kaper, A. E. Koshelev, G. K. Leaf, V. M. Vinokur, Phys. Rev. B 2000, 61, 1446.
[17] G. R. Berdiyorov, M. V. Milošević, F. M. Peeters, Phys. Rev. Lett. 2006, 96, 207001.
[18] D. Y. Vodolazov, Phys. Rev. B 2013, 88, 014525.
[19] I. A. Sadowskyy, A. E. Koshelev, C. L. Phillips, D. A. Karpeev, A. Glatz, J. Comp. Phys. 2015, 294, 639.
[20] I. A. Sadowskyy, L. A. Sadowskyy, C. L. Phillips, A. Glatz, Phys. Rev. B 2016, 93, 060508(R).
[21] I. A. Sadowskyy, A. E. Koshelev, A. Glatz, V. Orthalan, M. W. Rupich, M. Leroux, Phys. Rev. Appl. 2016, 5, 014011.
[22] V. Selvanamickam, Y. M. Chen, X. M. Xiong, Y. X. Xie, M. Martchevski, A. Ran, Y. F. Qiao, R. M. Schmidt, A. Knoll, K. P. Lenseth, C. S. Weber, IEEE Trans. Appl. Supercond. 2009, 19, 3225.
[23] J. L. MacManus-Driscoll, S. R. Foltyn, Q. X. Jia, H. Wang, A. Serquis, L. Civale, B. Maiorov, M. E. Hawley, M. P. Maley, D. E. Peterson, Nat. Mater. 2004, 3, 439.
[24] T. Haugan, P. N. Barnes, R. Wheeler, F. Meisenkothen, M. Sumption, Nature 2004, 430, 867.
[25] S. Kang, A. Goyal, J. Li, A. A. Gupud, P. M. Martin, L. Heatherly, J. R. Thompson, D. K. Christen, F. A. List, M. Paranthaman, D. F. Lee, Science 2006, 311, 1911.
[26] B. Maiorov, S. A. Baily, H. Zhou, O. Ugurlu, J. A. Kennison, P. C. Dowden, T. C. Holesinger, S. R. Foltyn, L. Civale, Nat. Mater. 2009, 8, 398.
[27] V. Selvanamickam, M. Heydari Gharahcheshmeh, A. Xu, E. Galstyan, L. Delgado, C. Cantoni, Appl. Phys. Lett. 2015, 106, 032601.
[28] A. Xu, V. Braccini, J. Jaroszynski, Y. Xin, D. C. Larbalestier, Phys. Rev. B 2012, 86, 115416.
[29] M. Toulemonde, S. Bouffard, F. Studer, Nucl. Instr. Meth. Phys. Res. 1994, 91, 108.
[30] R. Wheeler, M. A. Kirk, A. D. Marwick, L. Civale, F. H. Holtzberg, Appl. Phys. Lett. 1993, 63, 1573.
[31] Y. Zhu, Z. X. Cai, R. C. Budhani, M. Suenaga, D. O. Welch, Phys. Rev. B 1993, 48, 6436.
[32] L. Civale, A. D. Marwick, T. K. Worthington, M. A. Kirk, J. R. Thompson, L. Krusin-Elbaum, Y. Sun, J. R. Clem, F. Holtzberg, Phys. Rev. Lett. 1991, 67, 648.
[33] L. Civale, Supercond. Sci. Technol. 1997, 10, A11.
[34] L. Fang, Y. Jia, V. Mishra, C. Chaparro, V. K. Vlasko-Vlasov, A. E. Koshelev, U. Welp, G. W. Crabtree, S. Zhu, N. D. Zhigadlo, S. Katrych, J. Karpinski, W. K. Kwok, Nat. Commun. 2013, 4, 2655.
[35] L. Krusin-Elbaum, L. Civale, J. R. Thompson, C. Feild, Phys. Rev. B 1996, 53, 11744.
[36] L. Krusin-Elbaum, A. D. Marwick, R. Wheeler, C. Feild, V. M. Vinokur, G. K. Leaf, M. Palumbo, Phys. Rev. Lett. 1996, 76, 2563.
[37] W. K. Kwok, L. M. Paulius, V. M. Vinokur, A. M. Petrean, R. M. Ronningen, G. W. Crabtree, Phys. Rev. Lett. 1998, 80, 600.
[38] W. K. Kwok, L. M. Paulius, V. M. Vinokur, A. M. Petrean, R. M. Ronningen, G. W. Crabtree, *Phys. Rev. B* 1998, 58, 14594.

[39] A. Xu, L. Delgado, N. Khatri, Y. Liu, V. Selvamanickam, D. Abraimov, J. Jaroszynski, F. Kametani, D. C. Larbalestier, *Appl. Phys. Lett. Mater.* 2014, 2, 046111.

[40] A. Xu, J. J. Jaroszynski, F. Kametani, Z. Chen, D. C. Larbalestier, Y. L. Viouchkov, Y. Xie, V. Selvamanickam, *Supercond. Sci. Technol.* 2010, 23, 014003.

[41] O. Polat, M. Ertogrul, J. R. Thompson, K. J. Leonard, J. W. Sinclair, M. P. Paranthaman, S. H. Wee, Y. L. Zuev, X. Xiong, V. Selvamanickam, D. K. Christen, T. Aytog˘, *Supercond. Sci. Technol.* 2012, 25, 025018.

[42] W. E. Lawrence, S. Doniach, in *Proceedings of the Twelfth Conference on Low Temperature Physics*, (Ed: E. Kanda), Keigaku, Tokyo 1970, p. 361.

[43] B. Holzapfel, G. Kreiselmeyer, M. Kraus, S. Bouffard, S. Klaumunzer, L. Schultz, G. Saemann-Ischenko, *J. Alloys Comp.* 1993, 195, 411.

[44] T. Hwa, P. L. Doussal, D. R. Nelson, V. M. Vinokur, *Phys. Rev. Lett.* 1993, 71, 3545.

[45] D. Abraimov, A. Ballarino, C. Barth, L. Bottura, R. Dietrich, A. Francis, J. Jaroszynski, G. S. Majkic, J. McCallister, A. Polyanski, L. Rossi, A. Rutt, M. Santos, K. Schlenga, V. Selvamanickam, C. Senatore, A. Usoskin, Y. L. Viouchkov, *Supercond. Sci. Technol.* 2015, 28, 114007.

[46] V. Selvamanickam, Y. Chen, T. Shi, Y. Liu, N. D. Khatri, J. Liu, Y. Yao, X. Xiong, C. Lei, S. Soloveichik, E. Galstyan, G. Majkic, *Supercond. Sci. Technol.* 2013, 26, 035006.

[47] V. Selvamanickam, M. H. Gharahcheshmeh, A. Xu, Y. Zhang, E. Galstyan, *Supercond. Sci. Technol.* 2015, 28, 072002.

[48] V. Selvamanickam, M. H. Gharahcheshmeh, A. Xu, Y. Zhang, E. Galstyan, *Supercond. Sci. Technol.* 2015, 28, 104003.