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ABSTRACT
High-temperature superconductors (HTS) are materials that hold great promise for future particle-accelerator plants. YBa$_2$Cu$_3$O$_{7-x}$-based (YBCO) second-generation coated conductor coils can produce the intense field needed for ion confinement. Such coils can act as a radiation resistance magnet when exposed to radiation, and therefore, it is essential to better understand irradiation responses and defect creation in YBCO superconductors. The influence of laser or ion irradiation on the electrical characteristics of HTS has been studied previously; however, most results remain ambiguous and inconsistent. Degradation of or incremental changes in the critical current of the HTS tap are currently only observed and explained via irradiation dose. The relation between irradiation defects and macro-multi-field responses has yet to be established for YBCO tapes, for magnet design and operation. In this study, YBCO (2 G HTS) taps with Ag, Cu–Ag, and Cu protective cap layers were selected as targets of Nd-laser irradiation, at varying power. Irradiation defects were formed in YBCO taps, and irradiation dose was monitored as a function of superconducting properties and mechanical behaviors. The critical current and its N-values eventually degrade under intense Nd-laser irradiation, and the mechanical behavior of YBCO tapes shows nonlinear features after irradiation. Scanning electron microscopy and x-ray energy-dispersive spectrometry were applied to investigate the micro-defect changes that occurred in the taps after each Nd-laser irradiation dose. Micro-structural observations showed that the protective layers were critical for radiation resistance in YBCO taps. Furthermore, the macro-stress dependence of the critical current field was measured before and after Nd-laser irradiation to establish the relationship with micro-defect morphology by Nd-laser irradiation.

I. INTRODUCTION
HIAF (High Intensity heavy ion Accelerator Facility), a new international project, has been proposed by IMP (Institute of Modern Physics, Chinese Academy of Sciences) for heavy-ion related research. The facility would consist of two ion sources, a high-intensity Heavy Ion Superconducting Linac (HISCL), a 45 Tm Accumulation and Booster Ring (ABR-45), a multifunction storage ring system, and several high-energy targets. The facility is being designed to provide intense heavy-ion beams to investigate the structure of exotic nuclei, to learn more about astrophysical nuclear reactions, and to measure the mass of nuclei with high precision. Dense plasma will also be probed by the facility to elucidate the physics of nuclear fusion.

When the heavy-ion beam interacts with targets, they will be subjected to very strong radiation fields, and some neutron penetration of the blankets and plasma vacuum vessel is expected to occur. Thus, six quadrupoles and eight dipoles around the target are designed to be radiation tolerant or resistant. It is well known that second generation high-temperature superconductor (HTS) YBa$_2$Cu$_3$O$_{7-x}$ taps have a very large thermal margin due to the high critical temperature (>77 K), high upper critical field (>100 T),
and high tensile strength (>700 MPa) of the Hastelloy substrate.\textsuperscript{3,6} It is important that the conductor is co-wound with stainless steel, as the turn-to-turn insulator during a coil winding, so that the overall magnet has significant radiation resistance.\textsuperscript{7,8} Thus, in HIAF, the radiation resistant magnets around the targets will use YBCO non-insulator coil technology and operate at 25 K, cooled by helium gas. However, intense and continuous irradiation may still destroy YBCO coated conductor properties and microstructure. Significant challenges have always existed in the superconductor community, including obtaining knowledge of the physics that underpins the following: (i) the formation mechanism of defects that pin magnetic flux lines,\textsuperscript{9} the ambiguous and inconsistent relation between irradiation defects and electromagnetic responses,\textsuperscript{10} and the irradiation-defect dependence of the mechanical response.\textsuperscript{11}

The search for effective methodologies to pin vortices has been one of the most important issues in high-T$_c$ YBCO superconductors for research institutes and manufacturers because a high and dissipationless current can be achieved by pinned vortices.\textsuperscript{12–15} As is well known, the pinning of vortices in high-T$_c$ superconductors is very weak, and thus, strengthening vortex pinning in these materials by various sample treatments has been widely researched. Different types of irradiation, such as neutrons,\textsuperscript{16–19} electrons,\textsuperscript{20–22} protons,\textsuperscript{23} heavy ions,\textsuperscript{24} and lasers,\textsuperscript{25} have successfully produced non-superconducting structural defects of dimensions of the order $\xi$, the coherence length, which can act as very stable pinning sites. Most studies have only focused on producing a large $J_c$ enhancement in YBCO films by creating artificial pinning centers. Meanwhile, studies\textsuperscript{26–32} on particle-irradiated YBCO films have implied that the operating temperature has a significant influence on the irradiation intensity, and tapes are degraded at lower fluxes when the operating temperature is high.

Since the superconducting coil can work in the outside of the vacuum vessel for most accelerators, reacted neutrons or rays arrive at the superconducting coil through the vacuum vessel.\textsuperscript{33,34} The properties of superconducting materials will change, and the reacted neutrons or rays transfer their energy to the superconducting coil. Irradiation heating becomes the main quenching heat source, easily activating the superconducting materials.\textsuperscript{35} Thus, neutron-irradiation effects on practical superconducting wires have become important, relating to the establishment of large accelerator projects. To establish and confirm the irradiation and evaluation processes in ITER, the collaboration group was organized among the National Institute for Fusion Science (NIFS), National Institute for Materials Science (NIMS), and the Japan Atomic Energy Agency (JAEA). Neutron-irradiation effects on superconducting and insulating materials have been investigated in detail.\textsuperscript{36} Jirsa et al.\textsuperscript{37} studied the electromagnetic properties of a series of 21 tapes obtained from prominent global wire manufacturers. The tapes were tested before and after neutron irradiation using the magnetic induction technique and transport-current measurement. A significant enhancement of engineering currents was observed in magnetic fields above 0.5 T in all investigated tapes. Fischer et al.\textsuperscript{38} investigated flux pinning and radiation resistance by comparing the effects of neutron irradiation on tapes with and without artificial pinning centers. Kumakura et al.\textsuperscript{39} studied the sensitivity of critical currents to applied stress in neutron-irradiated YBCO tapes in liquid nitrogen. The high neutron-capture cross section of Gd and the resulting strong reduction of Tc seem to be responsible for the different stress dependencies of $I_c$ in irradiated Gd-123 coated conductors. Because of the limited neutron source, the similarities among the damaged structures of the produced materials, and the low induced radioactivity of the samples, important and alternative tools—heavy ion, electron, and laser irradiation—have often been used to simulate the radiation damage caused by energetic neutrons in superconducting materials.\textsuperscript{39,40} Suvorova et al.\textsuperscript{41} investigated the effects of $107$ MeV $^{36}$Kr\textsuperscript{42} ion irradiation on YBCO-based second-generation coated conductors using a combination of transmission electron microscopy, diffraction, and x-ray energy dispersive spectrometry. Upon heavy-ion bombardment, the micro-structure showed a significant enhancement of YBCO/buffer oxide adhesion to the Hastelloy substrate, a reduction in stress, and the formation of a crack-free structure in the YBCO layer. The use of low-dose irradiation enables the critical current to be increased without lowering the transition temperature. Kirschner et al.\textsuperscript{43} improved the superconducting properties of YBCO specimens by high-energy heavy-ion irradiation. The average values of intragrain critical current density grew by 37%–51%, and a slight increase in the critical temperature of 1–2 K was also observed. Although laser interaction that mainly produces heat effects is completely different from neutron or other ions irradiation effect, under such thermal conditions, the surface is still expected to experience the non-equilibrium state, thus obtaining new functional properties, the surface of oxide material may contain many pores, micro-cracks, insulating phases, and impurities at the grain boundaries that will also modify similarly the sample’s critical current density. Thus, the influence of laser radiation on high-temperature superconductor (HTSC) characteristics has also been studied in previous papers, which can provide some reference on research methods for other ions irradiation.\textsuperscript{25–28} For example, Luctiv et al.\textsuperscript{25} studied the effect of different kinds of laser (Nd, CO$_2$, and ruby) irradiation on 123-YBCO, Bi-2212, and Bi-2223 and found an enhancement in critical current density $J_c$, but a suppression of $T_c$ because the fraction volume of diamagnetism inside the bulk superconducting sample decreased. Elsabawy et al.\textsuperscript{29} studied Nd-laser irradiation effects in lutetium thorium-co-doped-2212-BSCCO. Both bulk superconductivity and surface resistivity were measured to establish the promotion occurred on the superconducting features due to Nd-laser irradiation dose. In general, critical current or temperature degradation of the HTS-material subjected to ion or laser irradiation is observed, but a corresponding increase in critical current and temperature has also been observed.\textsuperscript{22,26,43} Thus, ion or laser irradiation enables modification of the microstructure and superconducting material properties. However, how macrostructural disordering of these irradiated defects presents itself in the incoherent interfaces of coated conductors, and how it correlates with macro-multi-field responses has not, until now, been clear, despite its effectiveness.

In the present work, we explore the effects of Nd-laser irradiation on the superconducting properties, microstructure, and macrostress dependence of the critical-current field of YBCO tapes. We present structural analysis results obtained at the micro level of irradiated YBCO samples with different protective layers. A strong enhancement in radiation resistance is found to be controlled by the protective layers, whose absorption rate of Nd-laser irradiation also decides the critical current of YBCO tapes. One important reason for our research is that, according to the best of our knowledge, an investigation of the irradiation-defect dependence of the
macro-performance for YBCO tapes has not been published until now. This study examines these phenomena by comparing the effects of laser irradiation on tapes.

II. EXPERIMENTAL DETAILS

Figure 1 shows the scheme for our multi-scales experimental research on Nd-laser irradiation effects in this work. Macro-responses and its micro-structure analysis in YBCO tap with different protective layers were carried out in detail. Furthermore, we will investigate the effects of critical current on the tensile stress considering the irradiated micro-defects’ morphology. It is very significant for understanding and establishing macro-current/stress-poly-crystalline microstructure relation for YBCO tape irradiation engineering applications.

A. Samples

YBCO taps were all from SuperPower® and consisted of a YBa$_2$Cu$_3$O$_{7-\delta}$ superconducting layer on an IBAD (ion beam assisted deposition) template. Notably, YBCO taps with different protective layers were used in our study: SCS12050-AP tape with a 20-μm Cu cap layer and a width of 12 mm, SF12050-AP tape with an 8-μm Ag cap layer and a width of 12 mm, and SF6050-AP tape with a 20-μm Cu–Ag cap layer and a width of 6 mm. The total thickness of the Ag layer, 2 μm, the YBCO film, 1 μm, and the maximum thickness of the cap layer, 20 μm, was located at the projected range of Nd-laser irradiation (~5 μm–300 μm for the sample studied). Samples were cut from the same spool, and before laser irradiation, each sample was checked by electromagnetic and mechanical measurements. Furthermore, three samples were used for each measurement and the results were averaged.

B. Laser irradiation source

An Nd-pulsed laser irradiation source was used in our study with a wavelength of 1.064 μm, pulse rate of ~10$^{-4}$ s$^{-1}$ to 10$^{-2}$ s$^{-1}$, and achievable spot dimension of ~0.18 μm. The target was irradiated by different doses of irradiation, which was carried out in air without any heating. The energy density of the laser was sufficient to homogeneously melt the surface and superconducting layers. Fresh YBCO taps with different protective layers were used for each given dose (0.05–1.4 MJ/cm$^2$) by adjusting the power of the laser irradiation source. In addition, the YBCO film may lose oxygen at above 623 K, in our experiment, short laser interaction time can be adjusted (μs–ms), and laser spot dimension is also controlled according to the laser irradiation source used (~μm). Although the temperature of the limited laser spot dimension can be estimated as ~1000 K, heat can be diffused quickly in air, the whole sample might not be heated up, and thus, it can be assured that degradation of I$_c$ comes only from short laser pulse interaction for the tested whole samples.

C. Superconductivity and its multi-field measurements

A versatile test facility capable of providing a cryogenic-electromagnetic multifield was used for superconducting and multi-field-dependent measurements. The facility consisted of a 3.5-T background superconducting magnet, cryogenic Dewar vessel, mechanical loading system, reaction frame system, multi-field measurement, and data acquisition system. A direct-current four-probe method was used to measure I–V curves. The voltage contacts were glued with silver paste, allowing small positional rearrangements, considering the elongation. The tested I–V curves were calculated by a power law [$E \sim I/(I/I_c)^3$] in a double logarithmic plot using an electric field criterion of 1 μV cm$^{-1}$. The slope of these curves was defined as the n-value.

The Universal Testing Machine (UTM) in the test facility was used to interrogate the original and laser-irradiated YBCO samples located in a cryogenic Dewar vessel; the stress in the sample was measured by the reaction frame structure. During the tests, the samples were cooled to the superconducting state and mechanically loaded with axial tension and then electrically excited. The cycle was carried out repeatedly from the zero state to the targeted force. At each step, the self-field, I$_c$, was measured, and between each step, the stress was released and I$_c$ was remeasured. Low-temperature resistance strain gauges (KFL series, 4 mm × 2.7 mm, 120 Ω, KYOWA®) were attached along the length of the sample to detect axial strains. For accuracy, dummy gauges were pasted strictly on the same sample near the active gauge with the same orientation, exposed only to the thermal environment and electromagnetic field. To minimize thermal noise, a wireless strain acquisition system, with a

![FIG. 1. The scheme for experimental research on laser irradiation effects.](image-url)
D. Micro-structural measurements

Scanning electron microscopy (SEM) and x-ray energy-dispersive spectrometry (EDS) were carried out on samples using a Zeiss MERLIN microscope in electron imaging mode (0.65 mm spherical aberration, 1.2 mm chromatic aberration, 300 kV Schottky emission gun, 0.11 nm limit of information, and 0.17 nm resolution at the Scherzer defocus). The original and irradiated YBCO taps underwent dry mechanical polishing. YBCO, buffer oxide, and the substrate layers were observed using SEM and EDS before and after laser irradiation.

The distribution of elements in the YBCO composite tape, inside and around the defect areas, was measured using an EDS system in SEM bright-field and high angle annular dark-field (BF and HAADF) modes using a FEI Tecnai Osiris microscope. The study took place at the atomic scale to observe the presence of defects induced by laser irradiation.

III. RESULTS AND DISCUSSION

A. Macro-behavior measurements

The irradiated damage in local portions is responsible for degradation of the superconducting current. Figure 2 shows the I–V curves of a YBCO superconducting tap with a Cu cap layer, Ag cap layer, and Cu–Ag cap layer under laser irradiation. Before the occurrence of irradiation damage in each sample, the I–V curves all meet their original results. However, once damage occurs, in the I–V curve for the tested YBCO taps with different cap layers, the quench voltages generated at lower current were all observed. For example, above about 1200-mJ irradiation, irradiated YBCO superconducting taps with an Ag cap layer, Cu–Ag cap layer, and a Cu cap layer decrease to 95%, 78%, and 64% of the quench currents, respectively. Degradation of the superconducting current is associated with cap layer absorption, irradiated damage, and crystallization of the YBCO layer, and the cap layer also plays an important role in protecting the superconducting layer. In this respect, damage of the cap layer first occurs in the irradiated portion. When irradiated energy melts the cap layer, fracturing occurs in the YBCO layer. When irradiated damage occurs in one portion, crystallization of the superconducting layer occurs, as does the bypass of transport current in the neighboring superconducting zone; accordingly, the neighboring zone is more easily quenched than any other place. Such a process can be repeated until almost all the neighboring zones are quenched. Resistance sharing can also be conducted for the YBCO superconducting tape with an Ag cap layer at the initial phase of the I–V curves (see Fig. 3). Resistance sharing becomes enhanced with increasing irradiation energy.

The dependence of critical current on laser energy density in YBCO tapes with different cap layers is shown in Fig. 4. The data were measured at 77 K. The degradation of critical current with energy density was observed for the YBCO tapes with all cap layers. This behavior is found to be universal and not specific to a certain tape under an irradiation field and cryogenic conditions.

In this work, it is more interesting to compare the radiation energy of tapes with different cap layers. It is striking that the critical currents in the tapes with the Ag cap layer (SF12050-AP) drop below...
their initial values at lower laser radiation energy than in tapes with the Cu–Ag cap layer (SF6050-AP) and Cu cap layer (SCS12050-AP). It can be assumed that the critical current degrades at a specific laser defect density. Since the absorption rate of the Cu or Cu–Ag cap layer is higher than the one of the Ag cap layer, it is thus understandable that the Ag cap layer is prone to be damaged, leading to a more radiation defect density and re-crystallization for taps. The defect density may include pores, micro-cracks, and insulating phases existing at the grain boundaries, which will block current transport.

The N-value is an important superconducting parameter, which represents the homogeneity of characterized YBCO taps, as well as thermally activated depinning. N-values are also important for the evaluation of pinning mechanisms and pinning forces. In this work, n-value data from YBCO taps with different cap layers are tested and analyzed. From Fig. 5, it is clear that the N-values are weakened as the irradiation power density increases for YBCO samples. It shows a sharp drop of N-values for tapes with the Ag cap layer when the irradiation power density exceeds a critical value of 0.05 MJ/cm². In Fig. 5, the N-values obtained for tapes with Cu and Cu–Ag cap layers are, respectively, 18 and 21, when the irradiation power density is 0.2 MJ/cm². Thus, in studies of unsuccessful coil performance under irradiation, N-values could be one possible way to estimate the radiation energy introduced during coil operation. This could contribute to the continuing developments in anti-irradiation coil design and operation.

The nominal stress–strain curves of non-irradiated and irradiated YBCO samples with different cap layers were tested at 77 K. Primary mechanical properties, including tensile strength, yield strength, and elastic modulus, were extracted and reported. According to the measurements made on YBCO taps with different cap layers under varying irradiation energy density, it can be concluded that laser irradiation effects on the YBCO taps’ mechanical behavior do indeed occur. The main results are shown in Figs. 6–8.

Figure 6 plots the tensile strengths of YBCO taps with different cap layers vs laser irradiation energy density at 77 K. The figure shows that the ultimate tensile strengths of YBCO taps with Ag cap layers, Cu–Ag cap layers, and Cu cap layers all decrease with increasing irradiation energy. Under 0.5 MJ/cm², the tensile strengths of YBCO taps with Cu cap layers and Cu–Ag cap layers are about 7% and 6% lower than the pristine one at 77 K, respectively, and the values for YBCO taps with Ag cap layers are only about 1.4%. Figure 7 displays the yield strengths of YBCO taps with different cap layers vs laser irradiation energy density at 77 K, showing similar behavior...
for each tensile strength. These results can both be explained by the laser irradiation destroying most of the Cu cap layers and Cu–Ag cap layers due to the layers’ high absorption rate, which can affect the mechanical strength of YBCO taps.

The Young’s moduli of the YBCO taps with different cap layers are depicted in Fig. 8, which shows the non-dependence upon laser irradiation energy density. Stress tends to saturate after the linear relation during the initial stage in the tested specimens with relatively high strength. This indicates that irradiated damage extension occurs mostly in samples undergoing plastic deformation. This elastic constant dependence is necessary for the numerical stress analysis of YBCO taps with complex configurations under laser irradiation.

**B. Micro-structural measurements**

1. **Structural confirmation and visualization of YBCO taps**

To examine further the effects of Nd-laser irradiation on YBCO taps, in this section, YBCO taps with Ag caps were chosen mainly for micro-structural analysis. Figure 9 shows the superimposed spectra obtained from an irradiation-damaged and a non-damaged region. All spectral peak intensities measured in net counts in the non-damaged region, with a normal stoichiometric composition of YBCO taps, were higher compared with those in the damaged region. This can be explained by the composition in the irradiation region being altered by laser-beam etching, at high dose, and some elements can also increase due to the roughness induced.

Chemical micro-analysis of cross sections of the irradiated YBCO taps with Ag caps was carried out to characterize changes occurring in the YBCO layers and the Hastelloy substrate. The EDS elemental maps of interfaces at the Ag layer, YBCO layer, and at the Hastelloy substrate are presented in Figs. 10(a)–10(d). In Fig. 10(a), the distribution areas of Ag elements decrease with increasing laser irradiation dose. The Nd-pulsed laser beam penetrates the Ag layer down to the YBCO layer, with the Ag layer becoming almost damaged. In Figs. 10(b) and 10(c), the Ba and Cu elements in the YBCO layer clearly decrease with increasing laser irradiation dose, which is evidence of superconducting current and temperature degradation. Ni elemental maps show the Ni-enriched layer formed at the observation area, which can be explained by the YBCO layer having been partly penetrated—the Hastelloy substrate interface becomes visible [see Fig. 10(d)]. Thus, we can conclude that laser irradiation damages at high doses, reducing the number of Ba and Cu elements, which is responsible for degradation of the superconducting transport current. In addition, the irradiated YBCO taps as pre-cold-treatments at 77 K were also studied, with no change in their EDS elemental maps of the interfaces. It was observed that the effects of the cryogenic temperature did not play any role in the micro-properties of irradiated YBCO taps.
FIG. 10. EDS image of irradiated SF12050-AP with Ag (a), Ba (b), Cu (c), and Ni (d) elemental maps.
2. Structural measurements by scanning electron microscopy

Figures 11(a)–11(d) display the SEM images recorded for non-irradiated and irradiated YBCO superconducting taps with an Ag cap layer. From Fig. 11(b), it is clear that, above a 0.05-MJ/cm² laser irradiation dose, the sample surface is damaged, and clearly, the morphology of the YBCO layer surface experiences micro-point-crystallization. From Fig. 11(c), it is obvious that, above a 0.075-MJ/cm² laser irradiation dose, the morphology of the sample surface is completely changed again, as a result of melting and recrystallization caused by induced laser irradiation. Many individual micro-point-crystallizations begin to merge, and thus, strip-crystallization clearly appears in Figs. 11(c) and 11(d), which show the sample with the Ag layer surface after 0.1 MJ/cm² irradiation. Clearly, strip-crystallization eventually changes to blocky crystallization, and the morphology of crystallizations is directed and oriented to the thermal effects of the laser and melting. Recrystallization was also observed to occur at the YBCO surface and near surface layers based on the above EDS map analysis.

For comparison, Fig. 12 shows SEM images of the non-irradiated and irradiated YBCO superconducting tap with the Cu cap layer. The Cu cap layer has a higher absorption of the Nd-laser light, and thus, above 0.5 MJ/cm², the sample surface starts to become damaged—some granular crystals are observed. When the irradiation dose is increased, a brittle superconductive oriented crystal forms due to the recrystallization process. Block crystals were observed frequently and clearly under 0.75 MJ/cm² and 1 MJ/cm². The block crystals or defects can accumulate near grain boundaries, which may restrain superconducting current transport. Thus, this irradiation can effectively be blocked if tapes are wrapped in a suitable cap layer.

3. Multi-field behavior measurements

We also aimed to establish whether a multi-field dependent behavior existed for the irradiated YBCO taps. Thus, under self-field, $I_c$ measurements were carried out together with the tensile stress measurements to establish the dependence relation with the micro-defects’ morphology due to Nd-laser irradiation. Figure 13 shows the self-field $I_c$, dependence on stress for unirradiated and irradiated YBCO taps with Cu cap layers. The critical currents are normalized by the critical currents of the unirradiated sample in the 15 MPa tensile stress and at zero field. The stress dependence of $I_c$ in the sample has slight change after irradiation. Irreversible limits of $I_c$ for the unirradiated and irradiated samples with low energy occur around their upper yield strength. When the external irradiated density was improved, irreversible limits of $I_c$ were observed before samples’ yield strength. From Fig. 13, it can be seen that the crystallization formation also decides the initial amplitude of $I_c$ after destroying cap layers, point crystallizations will not almost affect $I_c$, and strip and blocky crystallization can be accumulated quickly at the interface of YBCO layers that restrain superconducting current by altering the orientations of the YBCO grains. This explanation seems consistent with Hensel’s predicted model that imposes the mechanical behaviors of the surrounding large-scale crystalline medium of YBCO account for its critical state. Furthermore, it is observed that the $I_c$ degradation rate will be enhanced with increasing laser irradiated damage density under tensile stress field. This phenomenon was interpreted mainly that damage regions can overlap under
plastic deformations, which cause not only the melting of new damage regions, in the repeated and even numerous rebuilding of old damage regions. In addition, the higher damage density may lead easily to the crack propagation under lower stress level due to merging of several damage regions, furthermore, it can enhance the $I_c$ degradation rate at any stress level. The more detailed multi-field mechanism may be captured in the future by well-designed irradiation experiments and effective multi-scale simulations under electromagnetic, cryogenic, and stress fields.

IV. CONCLUSIONS

The properties and micro-structure of YBCO taps with different cap layers were studied before and after Nd-laser irradiation. We showed that the applied energy of the Nd-laser resulted in decreases in the critical current and its $n$-values and that the mechanical behavior of YBCO tapes possessed nonlinear features after laser irradiation.

SE-microscopy and ED-spectrometry images showed that irradiation defects are crystallizations in the YBCO lattice, which accumulated near grain boundaries, restraining superconducting current transport. Irregular crystallization shape was observed in SEM images with increasing laser energy. EDS microanalysis also confirmed that the reduction in superconducting elements in the defect areas is evidence of superconducting current and temperature degradation for YBCO taps.

In this paper, an important improvement is that $I_c$–stress multi-field relations were measured to establish the relation on macro-behavior and the micro-defects’ morphology due to Nd-laser irradiation. Irreversible limits of $I_c$ for the non-irradiated and irradiated samples, corresponding to their yield strength, were observed. Since plastic deformation improved irradiated damage density, the $I_c$ degradation rate would be enhanced with increasing laser-irradiated damage density beyond yield stress.

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