Self Field Instability in High- J_c Nb₃Sn Strands With High Copper Residual Resistivity Ratio

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Abstract—High critical current density (J_c) Nb₃Sn conductor is the best candidate for next generation high field (>10 T) accelerator magnets. Although very promising, state of the art high- J_c Nb₃Sn strands suffer magneto-thermal instabilities that can severely limit the strand performance. Recently it has been shown that at 1.9 K the self field instability is the dominating mechanism that limits the performance of strands with a low (<10) Residual Resistivity Ratio (RRR) of the stabilizing copper. In this paper the self-field instability is investigated in high- J_c Nb₃Sn strands with high RRR. At CERN several state of the art Rod Re-Stack Process (RRP) and Powder In Tube (PIT) Nb₃Sn strands have been tested at 4.2 K and 1.9 K to study the effects on strand stability of: RRR, strand diameter and, strand impregnation with stycast. The experimental results are reported and discussed. A new 2-D finite element model for simulating magneto-thermal instabilities and its preliminary results are also presented. The model, which describes the whole development of the flux jump in the strand cross section taking into account the heat and current diffusion in the stabilizing copper, is in good agreement with the experimental data.

Index Terms—Instability, magnet, Nb₃Sn, superconductor.

I. INTRODUCTION

HIGH critical current density (J_c) Nb₃Sn conductor is the best candidate for next generation high field (>10 T) accelerator magnets. Although very promising, state of the art high- J_c Nb₃Sn strands suffer magneto-thermal instabilities [1]–[7] that can severely limit the strand performance [7]–[11]. The magneto-thermal instability produces a fast magnetic flux motion within the conductor associated with Joule heating (flux-jump) that can prematurely quench the superconductor. The flux-jump can be caused by a sudden redistribution of the persistent currents, ‘magnetization instability’ [1], [2], or by a sudden redistribution of the transport current, ‘self-field instability’ [3], [4]. The magnetization instability mainly depends on J_c , on the effective filament size (D_{eff}) and, on the value of the Residual Resistivity Ratio (RRR) of the stabilizing copper, while the self-field instability depends on J_c and the strand diameter. The effect of RRR on the self-field instability is not much studied in high- J_c Nb₃Sn conductor and is one of the topics of this paper.

Magnetization instability has been the primary cause of the limited quench performance (40–70% of the short sample limit) at 4.4 K of some Nb₃Sn high field magnets built at FNAL [12]

and LBNL [13], [14] in the early 2000s. These magnets were characterized by a large D_{eff} (70–100 μm), a moderately high J_c (1700–1900 A/mm² at 4.2 K and 12 T) and, a low RRR (<10). At present the problem of magnetization instability at 4.4 K is contained through an optimization of the heat treatments and cabling process that guarantee a high RRR (>150). Using such approach the U.S. LHC Accelerator Research Program (LARP) collaboration was able to build and test a few Nb₃Sn magnets that reached at 4.4 K more than 80% of the short sample limit and did not show evidences of magnetization instability. These magnets were based on the Nb₃Sn Modified Jelly Roll (MJR, $J_c \sim 1900$ A/mm², $D_{eff} \sim 70$ μm) strand [15] or on the Rod Re-Stack Process (RRP, $J_c > 2400$ A/mm², $D_{eff} \sim 70$ μm) strand [15]–[17] produced by Oxford Superconducting Technology (OST).

Recently, it has been shown that at 1.9 K the self field instability is the dominating mechanism that limits the performance of high- J_c Nb₃Sn strands with a low RRR (<10) [7]. It was also shown [7] that for RRP strand with low RRR: 1) the minimum quench current due to the self-field instability, that is the self-field stability current (I_{s-SF}), is lower at 1.9 K than at 4.2 K; 2) at 1.9 K the I_{s-SF} can be considerably lower than the critical current at 12 T. The self-field instability might be the cause of the limited quench performance at 1.9 K of the latest magnets based on the RRP conductor built by the LARP collaboration [15], [16], [18].

At CERN several state of the art high- J_c Nb₃Sn wires have been recently tested at 4.2 K and 1.9 K in order to establish if the conclusions drawn for samples with low RRR can be extended to samples with higher RRR values and to study the effects on strand self-field stability of RRR, strand impregnation with stycast and, strand diameter. The wires tested included RRP strands produced by OST and Powder In Tube (PIT) strands by ShapeMetal Innovation—European Advanced Superconductors (SMI-EAS). In this paper the experimental results are reported and discussed. A new numerical model for simulating magneto-thermal instabilities and its preliminary results are also presented. This model, based on the finite element method, simulates the whole development of the flux jump in the strand cross section taking in to account the heat and current diffusion in the stabilizing copper and the strongly non linear transition of the superconductor to the normal state.

II. SAMPLE PREPARATION AND MEASUREMENTS

The two types of strand used in this study, the RRP by OST and the PIT by SMI-EAS, were taken from the CERN inventory. The RRP strand (Billet 7419) was bought in the framework of the LHC superconducting undulator upgrade and consists of a

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TABLE I
STRAND PROPERTIES

Sample ID	I_c @ 4.2 K-12 T [A/mm ²]	B_{c2}^* @ 4.2 K [T]	J_c @ 4.2 K-12 T [A/mm ²]	RRR	D_{eff} [μm]	Strand diam. [mm]	Strand type	Cu/non-Cu
1	673	23.06	2580	120	80	0.8	RRP	0.927
2	690	23.56	2645	120				
3	697	23.94	2672	80				
4	669	24.54	2564	8				
5	777	24.5	2978	290				
6	790	24.92	3030	270				
7	744	24.13	2852	140				
8	417	23.4	2842	270	60	0.6	PIT	1.22
9	508	24.27	2236	27	30	0.8		

*Determined from critical current measurements

TABLE II
STRAND HEAT TREATMENTS

Sample ID	Low Temp. Plateau * [°C], [h]	Interm. Temp. Plateau ** [°C], [h]	High Temp. Plateau ** [°C], [h]	Atmosphere
1	-	-	695, 17	Argon
2			695, 17	
3			695, 25	
4			695, 100	
5	205, 72	400, 48	695, 10	Vacuum
6			695, 17	Argon
7			695, 17	
8			695, 10	Vacuum
9	-	-	675, 44	

*Ramps to low temperature plateau are equal to 25°C per hour

**Ramps to intermediate and high temperature plateau are equal to 50°C/h

0.8 mm wire with 54 superconducting sub-elements. The PIT strand is one of the prototype wire (Billet 215) developed by SMI-EAS in the framework of the Next European Dipole (NED) program [19] and it has 288 superconducting sub-elements and a diameter equal to 1.26 mm. In this paper the experimental results of 9 round strand samples, tested at CERN, are reported. All the samples were wound, reacted and, tested on grooved cylindrical Ti-Alloy barrels (ITER barrel). Two samples were drawn to reduce the strand diameter at the University of Geneva. The main sample properties are summarized in Table I.

The first set of measurements involves 4 RRP strands reacted in a way to have almost the same J_c with a significantly different RRR. The sample heat treatments are summarized in Table II. Samples 2 and 3 (see Table I) were tested two times: after the first regular tests where the strands were in direct contact with the helium bath, the samples were retested once covered with a thick layer (~ 1 mm) of stycast (sample 2) and a thick layer (~ 2 mm) of silicon grease (sample 3). The stycast in sample 2 was introduced to investigate the effect of different thermal boundary conditions in strands with a relatively high copper RRR while the grease in sample 3 to improve its mechanical stability. With the first set of measurements, samples with a RRR ranging from 8 to 120 were tested; in order to investigate the effect of higher RRR values a second set of 3 RRP strands (samples 5 to 7) were prepared and tested. Sample 8 is a RRP strand that was drawn in several steps to reduce the diameter from 0.8 mm to 0.6 mm and to experimentally study the improvement of the strand self-field stability by reducing its diameter. Sample 9 is a PIT strand that was also drawn to reduce the

diameter from 1.26 mm to 0.8 mm. This operation was necessary to experimentally study the self-field stability of the PIT strand because the premature quench current of the 1.26 mm PIT strand exceeds the limit (2 kA) of our apparatus for critical and stability current measurements.

The tests consisted in critical and stability current measurements at 4.2 K and 1.9 K. Initially the critical current (I_c) was derived through voltage-current measurements increasing the current in a constant applied magnetic field (V-I measurements). The critical current was measured, with steps of 0.5–1 T, from 12 T (maximum field available) down to the minimum field at which the strand is stable (B_S). For fields lower than B_S , the samples always have premature quenches due to magneto-thermal instabilities. The premature quench current during V-I tests (I_q) was measured at least 5 times at each magnetic field, covering the field range from B_S to 0 T with steps of generally 1 T. The set of measurements at each magnetic field was preceded by one or more quenches of the sample to remove the strand magnetization [7]. During V-I measurements, premature quenches of not magnetized strand are provoked by the self-field instability [7] hence these measurements were done to determine the self-field stability current (I_{s-SF}). The last part of the test consisted in determining the magnetic field at which the strand had premature quenches during voltage-field measurements obtained by sweeping the applied field (B_a) at a constant current in the strand (V-H measurements). This measurement was performed using the following procedure: 1) quench the sample at 0 T for 2 or more times to remove the strand magnetization; 2) inject a certain transport current in the sample; 3) increase the applied magnetic field with a ramp rate equal to 5 mT/s. This measurement was done to study the effects of strand magnetization on the stability current [7].

III. EXPERIMENTAL RESULTS

It was found through a semi-analytical model [7] that the self field instability is characterized by 3 stability regions: an ‘high field’ stable region where the conductor can reach its intrinsic critical current; an ‘intermediate field’ region where the premature quench current is higher than a certain minimum, $I_{qMin-SF}(B)$, and its value depends on the severity of the perturbation that initiates the magneto-thermal instability; a ‘low field’ region where the premature quench current value does not depend on the amount of the perturbation and a quench can occur as soon as the current is higher than $I_{qMin-SF}(B)$. In the next paragraphs the experimental results will be analysed dividing the data in these three field regions.

The results of the V-I measurements of samples 1, 3 and 4 are summarized in Fig. 1. These samples, all from the same billet, are characterized by a similar critical current and rather different RRR values (ranging from 8 to 120). In the ‘low field’ regions (0–3 T at 4.2 K and 0–7 T at 1.9 K for the 0.8 mm RRP strand [7]) the premature quench current due to the self-field instability is not much dependent on the RRR value at 4.2 K (Fig. 1(a)) while, at 1.9 K, the strand self field stability significantly improves increasing the RRR from 8 to 120 (Fig. 1(b)). In the ‘intermediate field’ region (3–8 T at 4.2 K and 7–12 T at 1.9 K for the 0.8 mm RRP strand [7]) it was not possible to find experimental evidence, both at 4.2 K and 1.9 K, of the improvement

Fig. 1. I_c (or I_q when $B < B_s$) during V-I measurements of samples 1-3-4 (0.8 mm RRP with RRR ranging from 120 to 8) at 4.2 K (plot a) and 1.9 K (plot b). Sample 3 was tested a second time with silicon grease around the strand to reduce strand micro-motion. Only the minimum values of the quench current (between the 5 or more values measured at each field) are shown, to facilitate the plot reading. In Fig. 3 one can see the typical spread observed during V-I tests.

Fig. 2. I_c (or I_q when $B < B_s$) during V-I measurements of samples 5-7 (0.8 mm RRP with RRR ranging from 290 to 140) at 4.2 K (plot a) and 1.9 K (plot b).

of the quench performance increasing the RRR value. This is most likely due to: 1) the stronger sensitivity of the self-field instability, in the 'intermediate field' region with respect to the 'low field' region, to the amount of energy released by the perturbation that initiates the magneto-thermal instability and; 2) the difficulty of exposing all the samples to exactly the same perturbation spectrum. This idea is consistent with what was concluded by our previous model [7] and by the preliminary results of the new model presented in the last section of this paper. It is also supported by some experimental results. For example the sample 3, that had extremely low performance at 1.9 K (the quench current at 12 T was only 630 A that is 68% of the critical current), was retested once covered with grease to reduce the micro-motions of the strand and it had better quench performance only in the 'intermediate field' region (see Fig. 1(b) in the field range 10-12 T); a similar behavior was observed for sample 2 (Fig. 3(b)).

The results obtained by testing sample 3 shows clearly that a magnet based on this conductor and designed to reach its critical

current at 4.2 K when the peak field in the coil is 12 T might reach its critical current at 4.2 K but it might be limited by the self-field instability at 1.9 K where the quench current might be even lower than that one at 4.2 K. Recent LARP magnet tests showed exactly this behavior [18].

The V-I measurements at 4.2 K and 1.9 K of samples 5-7 (see Fig. 2) show that, at least in the 'low field' region, the strand self-field stability does not improve significantly increasing the RRR from ~ 140 to ~ 300 . Also for these samples, at 1.9 K, premature quenches at currents lower than the critical current at 12 T were observed. The critical current of samples 5-7 is about 7% higher than that one of samples 1-4 thanks to the low and intermediate temperature plateau during heat treatment.

The comparison between the results obtained testing sample 2 at first in direct contact with the helium bath and then covered with a 1 mm thick layer of stycast are summarized in Fig. 3. One can notice that the critical current did not change in the two cases showing that the sample was not damaged during the deposition of stycast and the stress in the strand did not change signifi-

Fig. 3. Test results of the sample 2 ($RRR = 120$) at 4.2 K (plot *a*) and 1.9 K (plot *b*); comparison between the case where the sample is in direct contact with the helium bath (full marks) and the case where it is covered by a thick layer of sty-cast (open marks).

Fig. 4. V-I measurements of samples 8 (0.6 mm RRP) and 9 (0.8 mm PIT) at 4.2 K (plot *a*) and 1.9 K (plot *b*); the critical and quench currents of each sample are normalized with respect to their own I_c at 12 T and 4.2 K and, compared with the results of the most stable (sample 5) between samples 1–7 (0.8 mm RRP).

cantly. The results at 4.2 K show that the stability of the sample was not modified (during both V-I and V-H measurements) by the different thermal boundary conditions. Differently, at 1.9 K, the sty-cast systematically reduced the quench current performance by about 10% in the ‘low field’ region (0–7 T) during the V-I measurements. Once again nothing can be concluded in the ‘intermediate field’ region. A layer of sty-cast thicker than 1 mm should not produce different quench performance indeed, assuming that the time constant of a magneto-thermal instability is generally shorter than 100 μ s (as predicted by the model discussed later), the thermal penetration thickness in the epoxy is smaller than 0.6 mm. It is also important to notice that the V-H measurements performed at 1.9 K (see B_q data in Fig. 3(b)) confirmed that magnetization instability does not play a significant role at 1.9 K even in strand with relatively high RRR.

Finally, in Fig. 4 the results of samples 8 and 9 are summarized. In these plots the quench current is normalized with respect to the strand critical current at 4.2 K and 12 T to better compare the stability of these two samples with respect to the most stable of the previous sample set (sample 5). Samples 8 and 9, drawn at the University of Geneva, had a critical current density similar to the one obtained from the original strands, hence the drawing process did not degrade their superconducting properties. Both the drawn strands are significantly more self-field stable than sample 5. This improved stability is due for sample

8 to the smaller strand diameter, as predicted by our previous model [7], and for sample 9 to the lower J_c and probably to the different strand layout. Indeed the PIT wire had a larger amount of copper in between the superconducting sub-elements, a larger copper to non-copper ratio and a smaller sub-element size with respect to the RRP strand, and all these solutions allow improving the dynamic stabilization of the strand.

For all the nine samples the self-field stability current (I_{s-SF}) occurred in the ‘intermediate field’ region and is lower at 1.9 K than at 4.2 K.

IV. MAGNETO-THERMAL INSTABILITY: A FINITE ELEMENT MODEL

In order to determine the conditions for a magneto-thermal instability to quench a superconducting strand, it is necessary to describe the entire development of the phenomenon (from the start of the flux jump to the quench) [7] and not only the start, as most of the models in literature do [1]–[4]. Indeed there are situations in which a flux jump starts and then stops before quenching the strand. In a previous semi-analytical model, the entire development of a magneto-thermal instability was simulated assuming that the heat and electrical current diffusion in the outer Cu shell and in the central Cu rod of the strand was negligible; this adiabatic model successfully predicted the minimum quench current due to the magneto-thermal instability

in high J_c Nb₃Sn strands with low RRR [7]. Nevertheless for Nb₃Sn strands with a sufficiently large RRR, that model underestimates the minimum quench current because the heat and current diffusion in the whole stabilizing Cu plays a significant role. In literature, no model was found that simulates the entire development of the magneto-thermal instability taking into account the heat and current diffusion in the whole stabilizing Cu. In order to fulfill this task a new numerical model was developed using the software package COMSOL [20] that allows solving, with a finite element method, general Partial Derivative Equations (PDE) coupled with the equations of the heat diffusion. The model is 2 dimensional and simulates the strand cross section taking in to account each sub-element; the superconducting sub-elements are embedded in a copper matrix and they are represented as continuous hexagonal superconducting regions with a circular central part made of bronze. It is assumed that the current flows only longitudinally and the transition from the superconducting to the normal state is described through the classical power law where the n -value changes with the critical current following the law presented in [21]. The model at first calculates the current distribution assuming a constant temperature then the thermal equations are coupled to the electro-dynamic equations, a short heat pulse (of the order of one microsecond or less) on the strand copper shell is provided as perturbation and the evolution of the temperature and current distributions is then calculated. The strand is assumed to be in direct contact with the helium bath and the heat transfer to He is considered. The magneto-thermal instability starts locally where a perturbation takes place and then propagates longitudinally. In order to account for the longitudinal heat flux that occurs during the development of the magneto-thermal instability an analytical model for the longitudinal heat diffusion was implemented in the finite element model. It was assumed that the perturbation acts over a certain length of the strand (of the order of few mm). A more detailed description of the model is beyond the scope of this paper and will be published elsewhere. With respect to the previous semi-analytical model, beyond considering the effects of the copper RRR, this new finite element model allows:

- 1) To consider the critical current distribution in the strand cross section;
- 2) To exactly calculate the distribution of the transport and magnetization currents in any load conditions (V-I measurements, V-H measurements, ramp of transport current and applied magnetic field at the same time, etc.);
- 3) To obtain the temperature distribution within the strand cross section;
- 4) To study the effect of the n -value on strand stability;
- 5) To study the amount of energy that is necessary to initiate the magneto-thermal instability.

Below some preliminary results obtained from this model are presented; the quench current due to the self-field instability is calculated for a 0.8 mm RRP strand that has the same layout and superconducting properties of sample 2 (see Table I). The current distribution is calculated assuming a constant applied field with no magnetization currents; this is practically the case of V-I measurements of not magnetized strand samples mounted on ITER barrels. In these calculations the n -value is set equal to 100 at 12 T and 4.2 K and, the perturbation acts over 4 mm of

strand, lasts one microsecond and its energy is always much less than the minimum quench energy.

Fig. 5(a) summarizes the results calculated by the model at 4.2 K for a strand with RRR equal to 8 and for different levels of perturbation energy. One can notice that the quench current is significantly dependent on the level of energy of the initial perturbation (the higher the perturbation the lower the quench current). This is true until the current reaches a certain minimum value of the premature quench current, $I_{qMin-SF}(B)$, below which it seems not to decrease independently from the strength of the perturbation. Furthermore, the lower is the magnetic field the lower is the value of the perturbation energy beyond which the quench current is equal to $I_{qMin-SF}(B)$. From this calculation one can conclude that for a certain perturbation energy, there are three stability regions: a 'low field' region ($0 < B < B_{LF}$) where the quench current is practically equal to $I_{qMin-SF}(B)$, a 'high field' stable region ($B > B_S$) where the conductor reach its intrinsic critical current and, an 'intermediate field' region ($B_{LF} < B < B_S$) where premature quenches occur but the quench current is higher than $I_{qMin-SF}(B)$. These stability regions were already predicted by our previous semi-analytical model: the novelty is that the values of B_{LF} and B_S depend on the level of energy of the initial perturbation. The new model also reveals that in the 'low field' region, for current values lower than $I_{qMin-SF}(B)$, partial flux jumps with no quench can occur, while in the 'intermediate field' region when a magneto-thermal instability is initiated it quenches the superconductor. This is consistent with experimental data [22] that show how premature quenches of superconducting strands were preceded by voltage spikes (partial flux jumps) only at low fields.

Fig. 5(b) shows the results at 4.2 K for different values of RRR. From this plot one can conclude that increasing the RRR above 120 has no significant stabilization effect, while passing from RRR less than 10 to 120 may have a significant stabilizing effect at high fields (at low fields the effect of RRR is rather limited). Nevertheless the stabilizing effect of RRR at high fields is drastically reduced when the energy released by the initial perturbation is sufficiently high, see Fig. 5(c).

In Fig. 5, plots *d*, *e* and *f* summarize the results calculated by the model at 1.9 K for the same cases of the plots *a*, *b*, *c*. Most of the conclusions drawn for the case at 4.2 K can be extended to the 1.9 K case. The only relevant differences are that: 1) at 1.9 K with respect to the 4.2 K case, the stabilizing effect of an high RRR is stronger at low fields (as strand measurements show) and weaker at high fields; 2) for a certain perturbation $B_S(1.9\text{ K}) > B_S(4.2\text{ K})$ and $B_{LF}(1.9\text{ K}) > B_{LF}(4.2\text{ K})$ (that is consistent with our previous model [7]). It is also interesting to notice that the minimum quench current for a certain field $I_{qMin-SF}(B)$ does not change much reducing the temperature from 4.2 K to 1.9 K: this is especially true when the RRR is equal to 8 (as it was predicted by our previous model) while, when the RRR is equal to 240, at low fields $I_{qMin-SF}(B)$ improves reducing the temperature (as it is observed in strand measurements).

From this calculation one can conclude that this strand, even with an extremely high RRR, can have premature quenches at 4.2 K and 1.9 K due to the self-field instability and in the field range 10–12 T the quench current value can be lower than the

Fig. 5. Quench currents due to the self-field instability calculated by the model for a 0.8 mm RRP strand at 4.2 K (plots *a*, *b*, *c*) and 1.9 K (plots *d*, *e*, *f*). The currents are calculated for different values of the copper RRR and of the energy released by the perturbation that initiates the magneto-thermal instability; a perturbation equal to 100% corresponds to an energy per strand unit length equal to $0.73 \mu\text{J}/\text{mm}$. The quench current is calculated with steps of 100 A and the I_q curves are polynomial fits of the results obtained for different magnetic field values.

strand I_c at 12 T and 4.2 K. Furthermore, depending on the energy released by the perturbation that initiates the magneto-thermal instability, the quench current can be lower at 1.9 K than at 4.2 K because at the lower temperature the self-field instability is more sensitive to perturbations.

V. CONCLUSIONS

Strand measurements show that at 1.9 K the self field instability is the dominating mechanism that limits the performance of high- J_c Nb₃Sn wires and the magnetization instability does not play a significant role. For these strands the minimum quench current due to the self-field instability, that is the self field stability current (I_{s-SF}), is lower at 1.9 K than at 4.2 K; at 1.9 K, even if the RRR of the stabilizing copper is high, the I_{s-SF} can be lower than the critical current (I_c) at 12 T and 1.9 K and, in case of strong perturbations the I_{s-SF} can be even lower than the I_c at 12 T and 4.2 K (see sample 3 Fig. 1). This behavior could explain the performance of the latest Nb₃Sn LARP

magnets based on the RRP conductor that, at 1.9 K, had equal or even lower quench currents with respect to the 4.4 K case [15], [16], [18]. Strand measurements also showed that: 1) covering the strand with a 1 mm thick layer of stycast reduced the quench current at 1.9 K of less than 10%; 2) the strand self-field stability can be improved by reducing the strand diameter or by reducing the critical current density.

A new numerical model for simulating magneto-thermal instabilities was developed. This model, based on the finite element method, simulates the whole evolution of the flux jump in the strand cross section. It takes into account the heat and current diffusion in the stabilizing copper and the strongly non linear transition of the superconductor to the normal state. Preliminary results, which were obtained simulating the quench current due to the self-field instability of a 0.8 mm RRP strand during V-I measurements, show that the new model is capable to effectively reproduce the experimental data over a wide range of RRR, J_c , strand geometry and perturbation spectrum. Consistently with the experimental data the model predicts that: 1) the self field

stability current (I_{s-SF}) occurs in the ‘intermediate field’ region; 2) if the perturbation energy is sufficiently high, however still much less than the minimum quench energy, it can be lower than the intrinsic critical current at 12 T even with high RRR values of the stabilizing copper.

From the experimental data and from the new model one can conclude that, at 1.9 K, increasing the RRR from 8 to 120 is beneficial for the strand self-field stability, while further increasing the RRR value does not produce significant effects.

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