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# Voltage-ampere characteristics of YBCO coated conductor under inhomogeneous oscillating magnetic field

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Direct current carrying type II superconductors present a dynamic resistance when subjected to an oscillating magnetic field perpendicular to the current direction. If a superconductor is under a homogeneous field with high magnitude, the dynamic resistance value is nearly independent of transport current. Hoffmann and coworkers [C. Hoffmann, D. Pooke, and A. D. Caplin, IEEE Trans. Appl. Supercond. **21**, 1628 (2011)] discovered, however, flux pumping effect when a superconducting tape is under an inhomogeneous field orthogonal to the tape surface generated by rotating magnets. Following their work, we report the whole Voltage-Ampere (V-I) curves of an YBCO coated conductor under permanent magnets rotating with different frequencies and directions. We discovered that the two curves under opposite rotating directions differ from each other constantly when the transport current is less than the critical current, whereas the difference gradually reduces after the transport current exceeds the critical value. We also find that for different field frequencies, the difference between the two curves decreases faster with lower field frequency. The result indicates that the transport loss is dependent on the relative direction of the transport current and field travelling, which is distinct from traditional dynamic resistance model. The work may be instructive for the design of superconducting motors.

It is well known that type II superconductors carrying a direct current present a resistance when they are under a perpendicular oscillating magnetic field.<sup>1-10</sup> Theoretical analysis<sup>1,3,7,8</sup> and experimental results<sup>1-7,10</sup> have shown that this resistance is due to flux flow caused by the interaction between the transport current and the applied field, and it is defined as dynamic resistance. The dynamic resistance value is proportional to the applied field magnitude and frequency if the superconductor is in a homogeneous field, and it is nearly independent of transport current if the field magnitude is high.<sup>7</sup> Hoffmann and coworkers<sup>11</sup> discovered flux pumping effect when a piece of superconducting stator connecting to a superconducting load was subjected to inhomogeneous magnetic fields orthogonal to the tape surface generated by rotating permanent magnets. Researchers from VUW<sup>12</sup> pointed out that dynamic resistance is the main limiting factor of saturation current in the flux pump. Concerning the open circuit voltage, they proposed a geometrical explanation considering screening current.<sup>13</sup> All these existing researches<sup>11-13</sup> focus on the flux pumping effect, where the superconducting stator generates dc power. In this letter, we extend the research to the V-I characteristics of YBCO Coated Conductor (CC) under rotating permanent magnets.

The experimental system is shown in Fig. 1(a), which is similar to rotating magnets flux pumps<sup>11-15</sup>. Eight Neodymium 52 magnets with a diameter of 20mm are uniformly mounted on a round copper disc. The outer diameter of the disc is about 81mm. All magnets were mounted with their north poles facing outward. The disc was fixed on a shaft, which was driven by a motor. A piece of *Superpower* 12mm width copper stabilized YBCO Coated Conductor (CC) tape was put beneath the disc. The tape was submerged in

Liquid Nitrogen (LN2) @77K. When the disc rotates, each magnet passes across the tape. The minimum gap between each magnet and the tape surface was 2mm, when the tape surface was facing a magnet's north pole. In this case, the maximum flux density was about 0.2T. The rotating speed of the shaft can be adjusted in the range of 0-15Hz, so the field frequency experienced by the CC tape was adjustable from 0 to 120Hz.

A main difference between this system and a rotating magnet flux pump is that the tape (or stator wire in flux pumps) is connected to a constant DC supply via a pair of current leads rather than to an inductive load. This set up allows us to investigate the V-I characteristics in a wide current range. A pair of voltage measurement leads was soldered to the center of the stabilizer layer of the tape, as shown in Fig 1(a). The distance between the two soldering points was 5cm. The voltage leads were closely twisted together to minimize noises and the ac signal generated by the rotating magnets. In between the voltage leads, parallel to the tape, a 4cm long cut was made in the center of the tape, which broke the superconducting layer. The voltage was sampled by an NI-6221 DAQ card with a sampling frequency of 2.4 kHz. The reference direction of voltage, current, and magnets' rotation is defined in Fig. 1(b), where CCW denotes counter-clockwise and CW denotes clockwise.

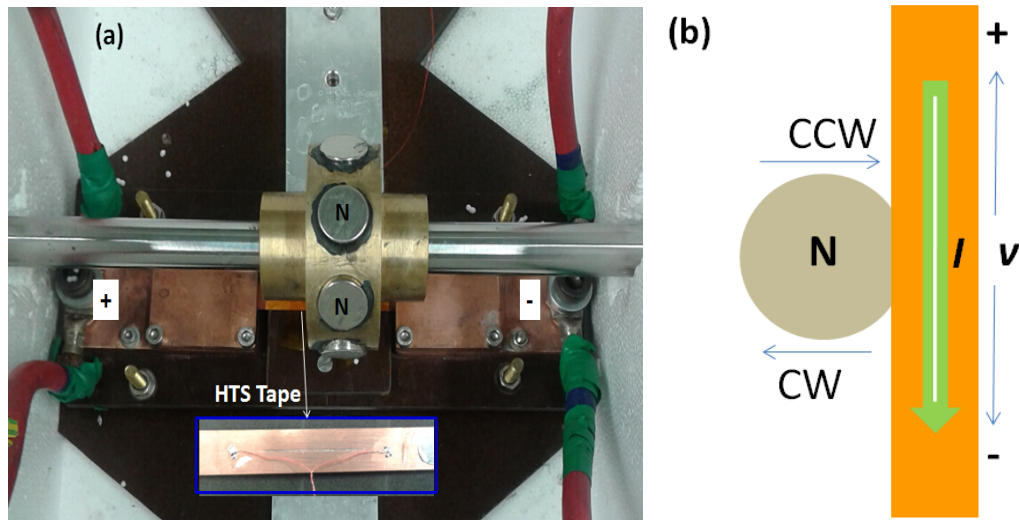


Fig. 1 Experimental system. (a) picture of the experimental system, where permanent magnets spin across a DC carrying YBCO CC. (b) reference direction of voltage, current, and magnets' movement. It is the bottom view of Fig. 1(a) so that the north pole of a magnet is seen, and the reference direction of voltage is marked in Fig. 1(a). CW refers to clockwise, and CCW refers to counter clockwise.

The static V-I characteristics of the tape were measured both before and after the cut. The V-I curve was measured with two different relative positions between magnets and the tape, i.e. the tape under the surface of a magnet or the tape under the gap between two magnets. As shown in Fig. 2, the critical current of the tape under a magnet is much lower than that under the gap. This is because of a strong field dependence of critical current density of YBCO. It can also be seen from Fig. 2 that the current capacity of the tape reduced slightly after cut.

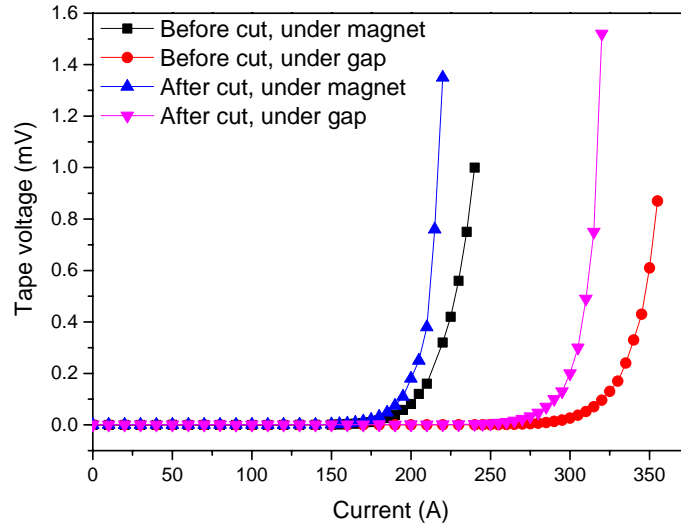


Fig. 2 V-I curve of the CC tape before and after the cut without magnets rotating.

In the rotating test, we firstly adjust the motor at a determined speed, then we ramp up the transport current from zero to 296A at an average rate of about 5A/s. Fig. 3 shows the V-I curves of the cut tape under rotating magnets with different speeds and directions. The data have been low-pass filtered by averaging samples in each 0.5s, so the ac component in voltage and current was eliminated. As can be seen from Fig. 3, when the transport current is less than 200A, all V-I curves are nearly linear. Under the same field frequency, both curves of opposite rotating directions tend to have the same slope although the intercepts differ from each other. When the transport current exceeds 200A, all curves become nonlinear. The difference of any two curves under the same field frequency begins to decrease, and in the end the two curves nearly overlap with each other.

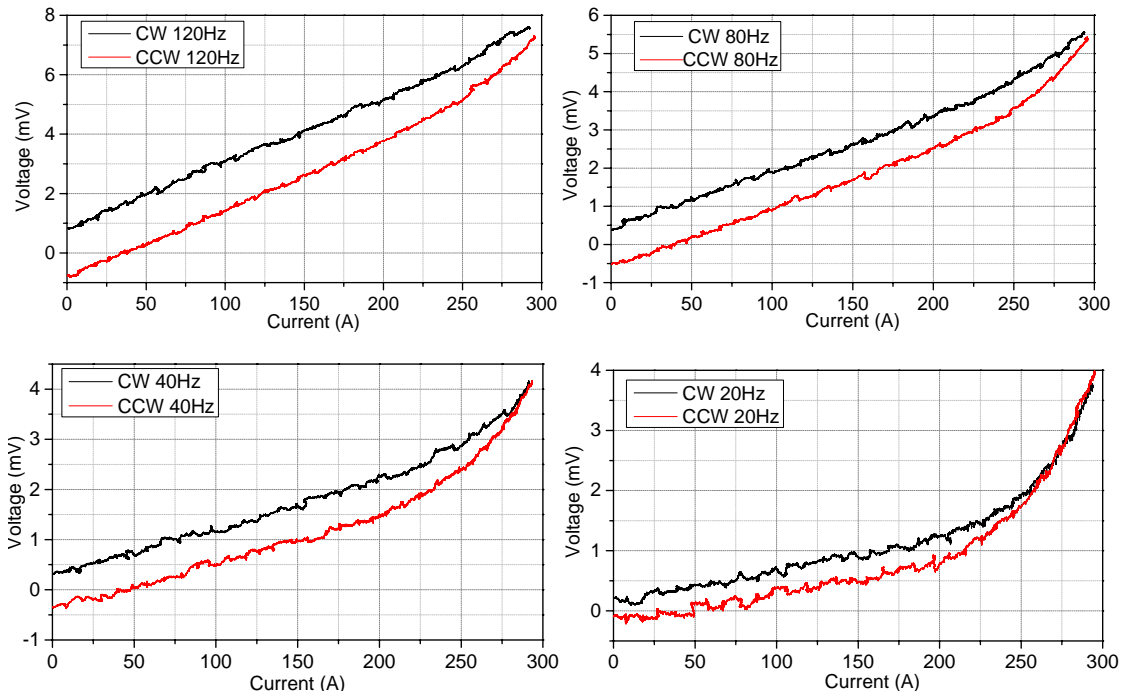


Fig. 3 V-I curves of the cut CC tape under magnets of different rotating frequencies and directions.

We re-plotted the V-I curves under 200A with a linear fitting, as shown in Fig. 4 and Fig. 5. It can be seen from Fig. 4 that for CCW rotation, all curves start with a negative open circuit voltage, and they cross together at  $V=0$ ,  $I=35A$ . From  $I=0A$  to  $I=35A$ , dc power consumed by the CC is negative, i.e. the CC actually works as a flux pump, although it is connected to a power supply rather than an inductive load. The result is consistent with the results in Ref. 12.  $I=35A$  is actually the largest achievable current if the CC is connected to a superconducting load rather than a power supply. It should also be noticed that at the point  $I=35A$ , no transport loss is generated although the superconductor is subjected to an oscillating field **orthogonal to its surface**. In comparison, Fig. 5 shows the V-I curves under CW rotating magnets. All curves start with a positive open circuit voltage, and the voltage increases linearly with current. The voltage is always positive, which indicates that the CC consumes dc power all the time. From Fig. 4 and Fig. 5, it is clear that the transport loss is dependent on the magnets' rotating direction, with a certain transport current. This is distinct from dynamic resistance model under homogeneous ac field. The result may be indicative in designing superconducting motors<sup>16</sup>, especially in reducing persistent current decay in rotor stack tapes<sup>17</sup> or coils<sup>18</sup> which are under ripple traveling waves.

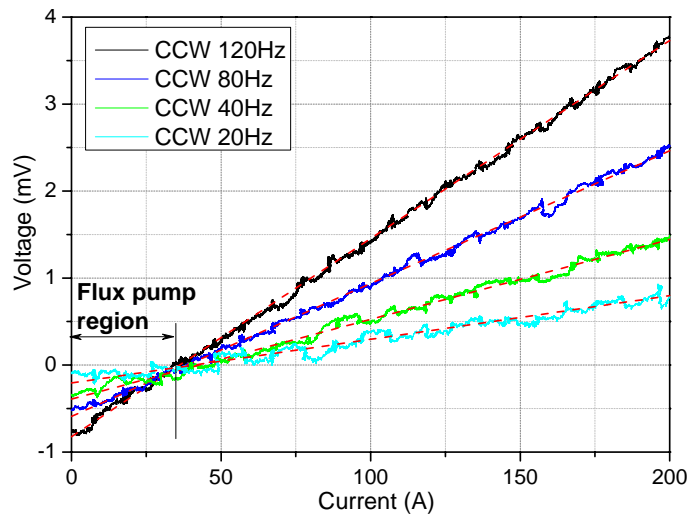


Fig. 4 V-I curves of counter clockwise rotating magnets together with linear fitting curves. For each field frequency, all curves start with a negative open circuit voltage. The curves cross together at  $v=0$ ,  $I=35A$ . From  $i=0$  to  $i=35A$ , it is actually working as a flux pump.  $I=35A$  is therefore the maximum current the device can output in a flux pump.

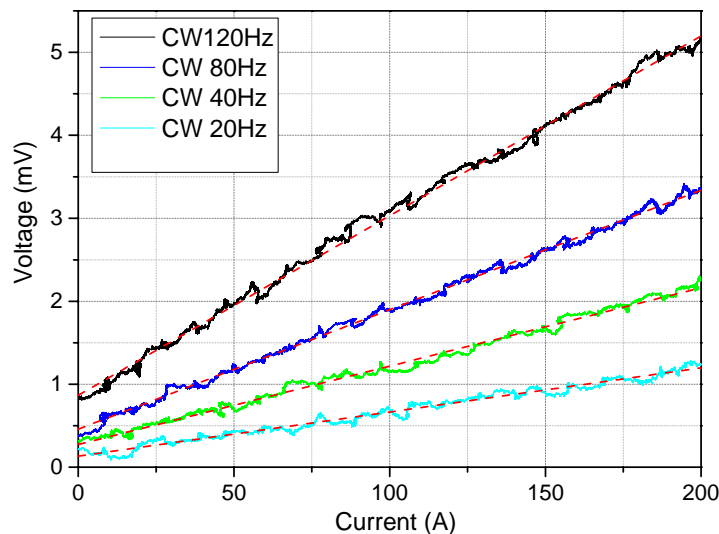


Fig. 5 shows the result of clockwise rotating together with linear fitting curves. For each field frequency, all curves start with

a positive open circuit voltage. For each curve, the voltage increases linearly with the current.

From the intercept and slope of fitting curves in Fig. 4 and Fig. 5, we can get the open circuit voltage  $V_{oc}$  and equivalent resistance  $R_{eq}$  of each curve, which have been plotted in Fig. 6 and Fig. 7. Both of the open circuit voltage and the equivalent resistance are proportional to field frequency. The result extended the previous researches on flux pump<sup>11-15</sup> which only generates dc power. The result shows that flux pumping effect exist even though the CC is open circuited, it also indicates that the open circuit voltage exist all the time no matter the CC generates dc power or consumes dc power.

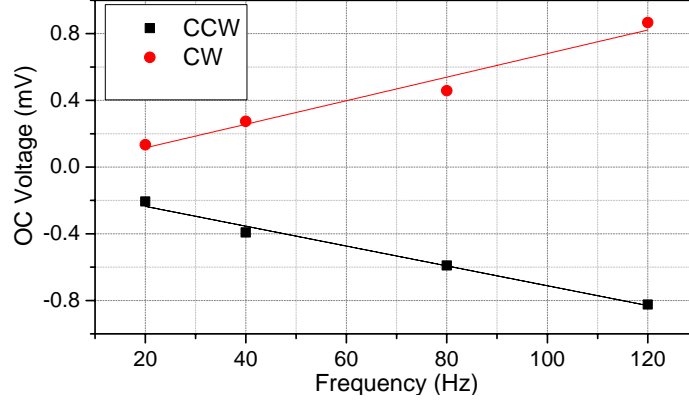


Fig. 6. Open circuit voltage of the YBCO CC tape under different field frequencies.

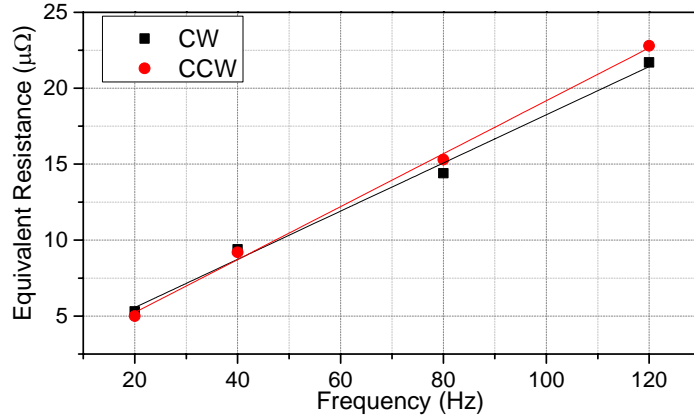


Fig. 7. Equivalent resistance of the YBCO tape under different field frequencies.

After the transport current exceeds 200A, two phenomena in the V-I curves in Fig. 3 should be noticed: the curve under lower frequency field tends to be more nonlinear although the absolute voltage is lower; the difference between the curves of CCW and CW rotating reduces faster with lower frequency.

In Ref. 13, the open circuit voltage of a flux pump was explained as: the screening current follows the position of the magnet; due to the geometry of the magnet and the CC width, the width of forward path and backward path of the screening current changes, thus resulting in a rectifying effect. In our experiment, however, the tape was cut, and therefore a barrier occurs in the middle of the tape, and the screening current distribution is different from that described in Ref. 13. The screening current tends to more locally circulate either side of the cut, rather than entirely circulate a loop round the cut. Therefore, the current density inside the tape will cannot be inversely proportional to the angle of the magnet which has been described in Ref. 13.

The general explanation for the dc voltage of type I and type II superconducting films under travelling magnetic field has been reported in Ref. 19, 20. The dc open circuit voltage can be expressed as<sup>20</sup>:

$$V_{DC} = \frac{1}{T} \int_0^T \frac{-d\Phi / dt}{R_1(t) + R_2(t)} R_2(t) dt \quad (1)$$

Where  $T$  is the ac period of applied travelling field,  $\Phi$  is the flux into the superconducting film due to external field excitation, and  $R_1(t)$  and  $R_2(t)$  represent the time varying resistances of the two edges of the film. The origin of the resistances is flux motion. The physics of Eq. 1 is that if more flux enters the film from one edge than that leaves the same edge, a dc open circuit voltage will appear. For a CC transporting a current  $I$ , when it is under a perpendicular ac field, two kinds of flux motion occur<sup>4,10</sup>. When  $I \ll I_c$ , the pinning energy<sup>21</sup> is large so the flux motion is mainly caused by the interaction between the ac field and transport current  $I$ , i.e. dynamic resistance<sup>1-10</sup>; whereas when  $I$  approaches or exceed  $I_c$ , the pinning energy becomes low, the superconductor will be in flux flow region. Therefore, we propose the following model to explain the result (Fig. 8).

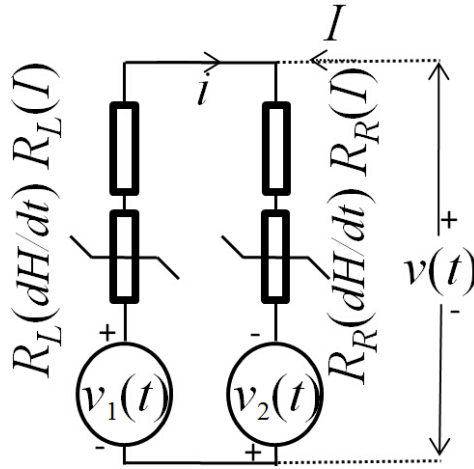


Fig. 8 Equivalent circuit model for the CC transporting a dc under rotating magnets. Where  $i$  represents the screening current circulating the cut and  $I$  represents the transport current,  $v_1(t)$  and  $v_2(t)$  represent EMFs<sup>20</sup>. Each edge of the tape can be considered as two resistances in series,  $R_L(dH/dt)$  and  $R_R(dH/dt)$  represent equivalent resistances of flux flow caused by the interaction between the local ac field and  $i$ ,  $R_L(I)$  and  $R_R(I)$  can be considered as flux motion caused by de-pinning.

Each edge of the CC can be considered as a sum of two resistances:

$$R_{edge}(t) = R_{edge}(dH/dt) + R_{edge}(I) \quad (2)$$

Where  $R_{edge}(t)$  represents the total resistance of either edge, and  $R_{edge}(dH/dt)$  is the dynamic resistance of each edge which is caused by the interaction between the changing field at each edge and the global screening current  $i$ ,<sup>20, 22</sup> and  $R_{edge}(I)$  is caused by the de-pinning effect. When the transport current  $I$  is smaller than 200A, the pinning energy is large, so  $R_{edge}(I)$  is negligibly small compared with  $R_{edge}(dH/dt)$ . In this case, the open circuit voltage is the same as we reported in Ref. 20. Most flux will enter the CC from one edge and leaves at the other, so the open circuit voltage magnitude is proportional to field frequency and its polarity is determined by field traveling direction, as described by Eq. 1. When the transport current  $I$  exceeds 200A,  $R_{edge}(I)$  gradually increases and become the dominant resistance. In this case, when a magnet is approaching the CC, flux flows into the CC from both edges; when a magnet is leaving the CC, flux flows out of the CC from both edges. The net flux flow across each edge reduces with the increase of the de-pinning flux flow. For a lower frequency field, the values of  $R_{edge}(dH/dt)$  is smaller, so the effect of de-pinning flux flow is more significant. Therefore, the difference between the two V-I

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curves under opposite rotating directions decreases faster at lower field frequencies.

The equivalent resistance is approximate to the parallel of edge resistances. When the transport current is low, the equivalent resistance is mainly contributed to by dynamic resistance, which is proportional to field frequency, and is independent of transport current. In this case, the V-I curves tend to be linear. When the transport current is high, de-pinning flux flow dominates the equivalent resistance and the curves become nonlinear. Similar results can be found in Ref. 2, 4, where the superconductor is more nonlinear due to lower dynamic resistances.

In conclusion, we conducted experiments on the  $V$ - $I$  curve of YBCO coated conductor under permanent magnets with different rotating speeds and directions. The results are distinct from the V-I curve of a superconductor under homogeneous ac field<sup>2,4-7</sup>. When the transport current is under the critical current, all curves can be well fitted by an open circuit voltage and a constant equivalent resistance, both of which are proportional to field frequency. Yet the polarities of the open circuit voltage are opposite with opposite rotations. All curves become nonlinear after the transport current exceeds the critical value, and the difference between the two curves under opposite rotations reduces with the current increase. The curves under lower frequency field tend to be more nonlinear, and the difference between the two curves under opposite rotation decreases faster. We have proposed a circuit model that is a combination of a flux pump model<sup>20</sup> together with flux motion characteristics in dc carrying superconductor under an ac field<sup>10</sup>. Two factors contribute to the flux flow in the CC<sup>10</sup>: when transport current is low, the pinning energy is high, and the flux flow is due to the interaction between the screening current and the local ac field, which is dependent on field rotating direction; when transport current is high, flux flow is caused by de-pinning, which is independent of field rotating direction. The result may help design superconducting motors to minimize current decay in the rotor.

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