Coupling Current and Hysteresis Losses of Bi2212 Round Wires with Twisted Filaments

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Abstract

AC loss measurements have been carried out on Bi2212 round wires of different twist pitches. With systematical variation of sample temperature (5 K – 70 K) and ac field amplitude (≤0.2 T) as well as frequency (20 Hz – 2 kHz), this work shows (a) the full coupling of the non-twisted wire, (b) the uncoupling of sub-wires by twisting at moderate pitch up to 12 mm, (c) a relatively short time constant of milliseconds for the coupling current due to a high transverse resistivity, and (d) an effective (de)coupling diameter of 0.4mm about 1.6x of sub-wire bundles. The results suggest a promising potential for improving filament decoupling.

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Abstract—AC loss measurements have been carried out on Bi2212 round wires of different twist pitches. With systematical variation of sample temperature (5 K – 70 K) and ac field amplitude (≤0.2 T) as well as frequency (20 Hz – 2 kHz), this work shows (a) the full coupling of the non-twisted wire, (b) the uncoupling of sub-wires by twisting at moderate pitch up to 12 mm, (c) a relatively short time constant of milliseconds for the coupling current due to a high transverse resistivity, and (d) an effective (de)coupling diameter of 0.4mm about 1.6x of sub-wire bundles. The results suggest a promising potential for improving filament decoupling.

Index Terms—Superconducting Magnets, High Temperature Superconductors.

I. INTRODUCTION

B I2212 ROUND wire has become an exciting prospect [1]-[3] for high field magnets above 25 T, going beyond the practical limit of start-of-the-art Nb_3Sn conductors. The performance of Bi2212 conductors has seen a phenomenal increase as the results of high pressure processing [4] and coordinated material research. The round wire configuration of Bi2212 brings substantial advantages over other high temperature superconducting (HTS) tapes, especially in terms of coil manufacturing and filament refinement for large numbers and small sizes. To fully utilize the benefit of small filament size for field quality and cryogenic stabilization, filament twisting is a crucial technical prerequisite. The main challenges are the minimization of critical current degradation and a sufficiently high transverse resistivity to ensure consistent filament uncoupling over long lengths. The fabrication of Bi2212 wires with twisted filaments with clear indications of successful filament uncoupling has been reported recently by Miao [5]. The present work is devoted to a detailed study of ac losses in Bi2212 round wires of different twist pitches. The main objectives are the characterization of filament decoupling at different pitch and operating conditions and identification of the effective coupling diameter and the time constant of the coupling current.

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subsequently used for further restacking to yield conductors of a few thousand filaments. The wires could be twisted to a well-defined pitch while being drawn to the final diameter after the last restacking step.

The wires used in the present study had 1530 filaments in an 85x18 configuration of restacking 18 sub-wires of 85 filaments. A solid silver wire was placed at the centre in order to maintain the hexagonal symmetry of the final stacking and to provide further cryogenic stabilization. The wires had an outer diameter of $D = 1.2$ mm with twist pitches L_p of 8 mm, 12 mm and "infinity" (not twisted). The wire cross-section shown in Fig. 1(a) indicates an outer silver sheath of 0.1 mm thick, an inner diameter of $D_i \sim 1.0$ mm, and an average sub-wire diameter of $D_{sw} = 0.25$ mm. In the X-ray tomographic images shown in Fig. 1(b)-(c), the superconducting filaments (volumes in red) in one of the sub-wires are rendered over a length of ~1/6 the twist pitch.

B. AC Loss Measurements

The present study focuses on the coupling current and hysteresis losses due to a sinusoidal external magnetic field [6], which was produced by an electromagnet with two symmetric air-gaps for the specimen and reference respectively. The electromagnet was able to provide fields up to 0.2 T in amplitude and 2 kHz in frequency. The air gaps were able to accommodate samples up to 5 mm thickness, 15 mm wide, and 100 mm long. The length was a crucial requirement for investigating the (de)coupling of superconducting filaments. The present set-up allows the access to coupling current time constants in the millisecond regime.

The samples were cooled via a solid sapphire link to a GM cryo-cooler. The working temperature range is between 3 K and 100 K.

The losses due to the ac magnetic field was measured using a simple saddle-like pick-up coil placed around the conductor. The symmetry of the dual air-gap design ensured an accurate phase measurement from the reference coil in the other air-gap. The pick-up voltages were measured using a digital lock-in amplifier to a noise floor < 10 nV and at a phase angle resolution of 0.001°.

C. Methodology and Limitations

The use of a sinusoidal external ac field in this study was not because of a misguided anticipation of electrical power applications for the Bi2212 round wire. Instead it is designed for a detailed probe of the coupling current over a wide range of frequencies which are inaccessible in the standard field sweep magnetization measurement. The drawback of the ac field approach is the lack of dc magnetic field relevant to the intended operating conditions. This is due to the obvious difficulties of integrating an ac magnet suitable for a significant transverse sample length (>~100 mm) necessary for coupling current studies. As the results presented here will show, such a limitation have been mostly mitigate by substituting magnetic field with temperature, which affects the conductor critical current in a similar manner.
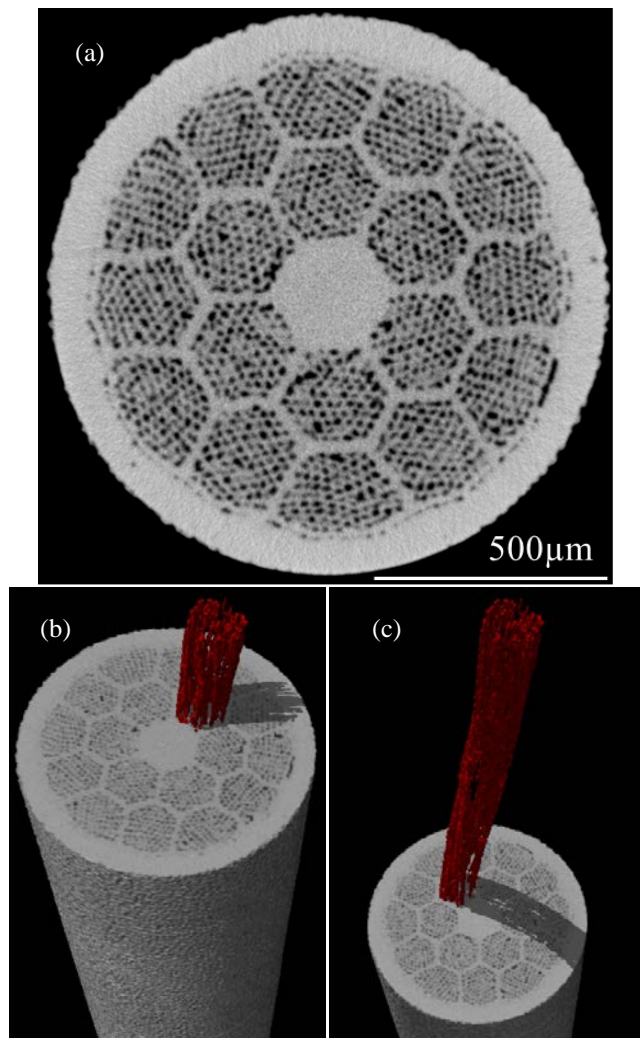

Fig. 1. (a) Cross-section of a Bi2212 round wire of 1.2 mm diameter with an 85x18 configuration. (b)-(c) X-ray tomographic images of the wire with the superconducting filaments in one of the sub-wires rendered volumetrically over a length of $L_p/6$.

II. EXPERIMENTAL

A. Bi2212 Round Wires

Oxford Instruments Superconducting Technology (OST) has established a promising manufacturing route to produce silver sheathed Bi2212 round wires [5] with the powder-in-tube method. Multi-filamentary wires were produced by packing single-core wires in a hexagonal configuration and

For each temperature T, the overall ac loss in an external field $B_0\cos(2\pi ft)$ was measured by sweeping either the field amplitude B_0 at a given frequency or f at a constant B_0.
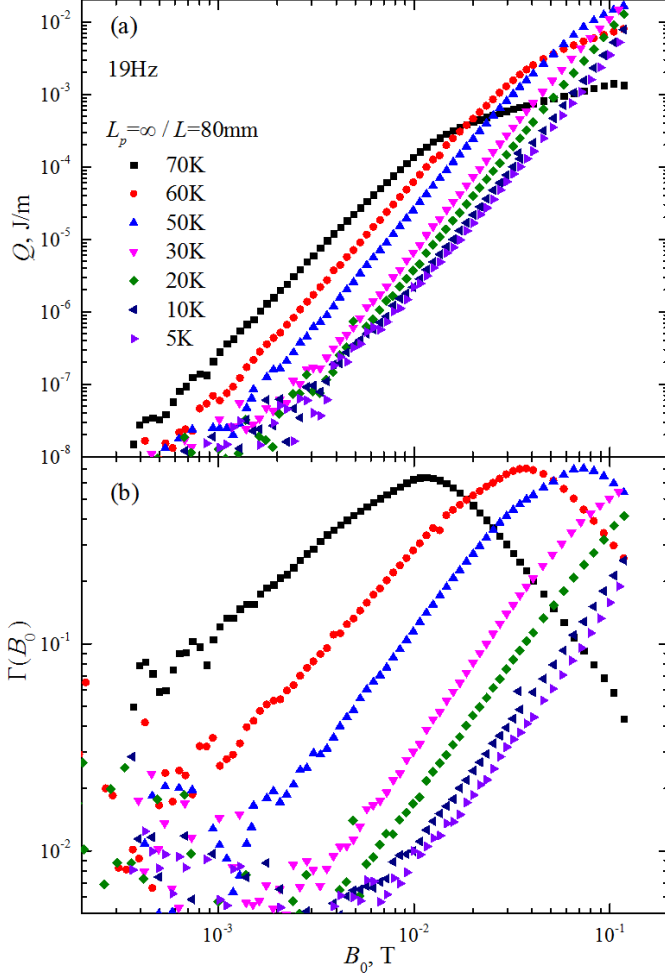

Fig. 2. (a) Losses per cycle and (b) the corresponding loss factor of a non-twisted Bi2212 wire as a function of ac field amplitude B_0 at different temperatures between 5 K and 70 K.

III. RESULTS AND DISCUSSION

In simple conductors of a monolithic superconducting core or fully coupled superconducting filaments, the ac loss is dominated by the flux pinning induced magnetic hysteresis, which has been well understood. Fully filament coupling is expected when the conductor length exceeds the Rutherford uncoupling length criterion [7]:

$$L_c = 4\sqrt{\frac{a\rho_m \lambda J_C}{\dot{B}}}$$

(1)

where a is the radius of either individual filaments or sub-wire bundles, ρ_m is the matrix resistivity, λ is the superconductor fill factor (λ=1 for coupling among individual filaments), J_C is the superconductor critical current. The average field sweep rate is approximately $\sqrt{2}\pi f B_0$. For the Bi2212 wires in discussion here, the critical coupling length is just ~75 mm for a high end J_C=5000 A/mm^2 filled at 25% (λ=0.25) within the 18 sub-wires of 125 µm diameter in Ag of ρ_m=2×10^{-10} Ωm in a small field of B_0=1 mT at 20 Hz. It can also be concluded that

(a) individual filaments (5-10 µm) within a sub-wire would be fully coupled and (b) decoupling should be observed in wires with a twist pitch shorter than the coupling criterion.
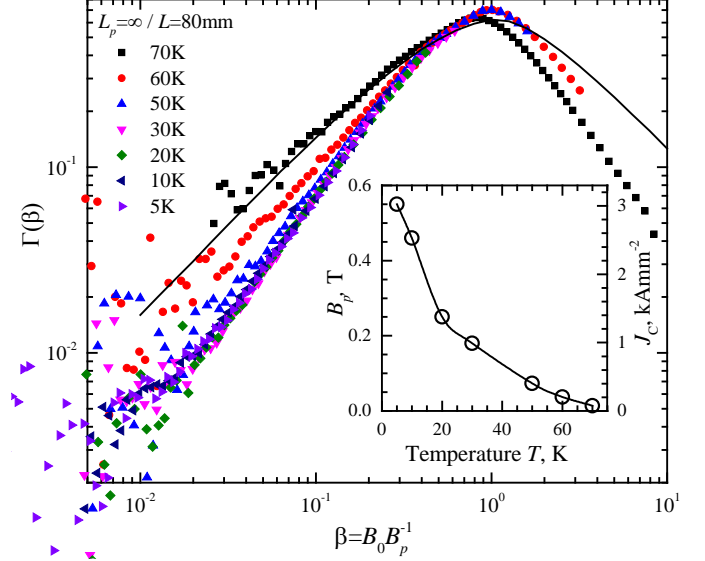

Fig. 3. Loss factor as a function of the normalized field $\beta = B_0/B_p$ for different temperatures between 5 K and 70 K. The inset shows B_p and the corresponding J_C as a function of temperatures.

A. Non-twisted Wires

Fig. 2(a) shows the ac loss per cycle Q at 19 Hz, as a function of field amplitude B_0, of an 80 mm long non-twisted Bi2212 wire at different temperatures between 5 K and 70 K. With the sample longer than the upper limit of Rutherford criterion, the wire is expected to behave as a monolithic superconducting cylinder with the 18 sub-wires fully coupled. The results shown in Fig. 2 indeed indicate a simple behavior of $Q \sim B_0^{3+}$ for $B_0 < B_p$ and $Q \sim B_0$ for $B_0 > B_p$, where B_p marks the fully penetration of the superconductor. The loss behavior is illustrated with further clarity in terms of loss factor $\Gamma = \mu_0 Q/(\frac{1}{2}B_0^2 A_Q)$ which peaks at B_p while increasing and decreasing with $\sim B_0^{\sim \pm 1}$ respectively on either side. A_Q is the loss producing cross-section area and the total wire area of $A_w = \pi D^2/4$ is used hereafter. The corresponding loss factor of the non-twisted wire in Fig. 2(b) confirms qualitatively the expected behavior for a monolithic superconductor. In addition, B_p can be identified directly above 30 K with the full penetration within the maximum field magnitude of 0.2 T.

The loss factor of a monolithic superconductor can be reduced to a single variable function of the normalized field $\beta = B_0/B_p$, as shown by the solid line in Fig. 3 for a cylinder in transverse field. The non-twisted wire data in Fig. 2(b) is shown in terms of β in Fig. 3. For temperatures ~> 30 K, B_p is given by the peak position in Fig. 2(b). As the temperature is reduced, Γ moves towards a steeper increase with β than linearity for $\beta < 1$ and converges to $\sim \beta^{1.3}$ for $T \leq 30$ K . It is therefore plausible, as shown in Fig. 3, to determine B_p for lower temperatures by scaling the corresponding data into a common curve. The full penetration field B_p, directly and indirectly obtained for temperatures above and below 30 K

respectively, can be found in the inset of Fig. 3. Note that B_p also leads explicitly to the critical current density $J_C(T,B_p) = \lambda^{-1}\pi B_p(T)/2\mu_0 D_i$, as indicated by the inset right axis. The upturn of J_C below 20-30 K is consistent with the flux melting temperature of Bi2212 and J_C(5 K, 0.5 T) ~ 3000 A/mm^2 is in line with that of the witness samples.
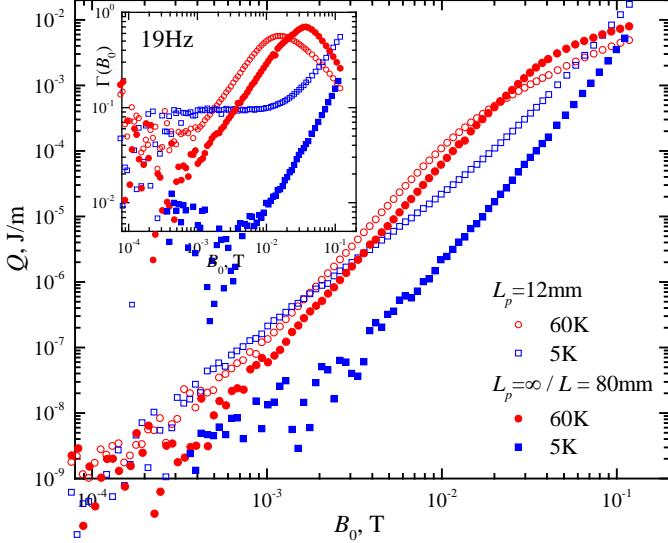

Fig. 4. The ac loss per cycle 5 K and 60 K (blue and red open symbols) of Bi2212 round wire with L_p = 12 mm is shown as a function of field amplitude B_0. The corresponding loss (solid symbols) of a non-twisted wire is also shown for comparison. The inset shows the loss factors of the same data set.
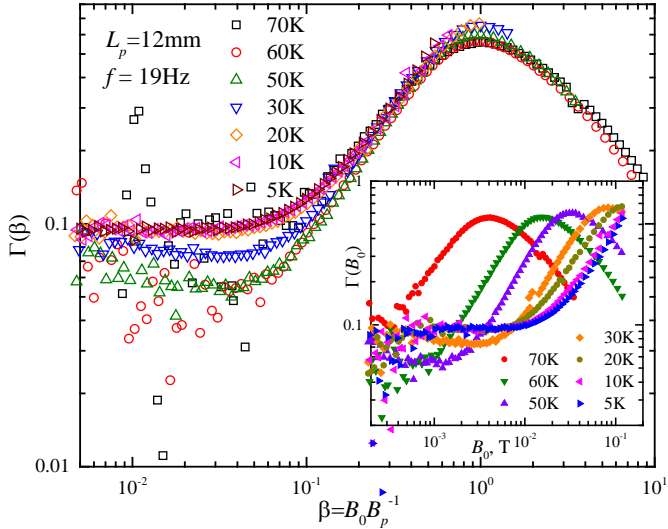

Fig. 5. Loss factor of a twisted wire with L_p=12 mm at different temperatures as a function of field amplitude B_0 (inset) and as a function of the normalize field β.

B. Twisted Wires

Compared with the full coupling of sub-wires in the non-twisted wire, Fig. 4 shows a markedly different behavior for a wire twisted at a pitch of 12 mm. At 60 K, the twisted wire shows a reduced B_p, and a lower loss above B_p than the non-twisted wire. It is the desired outcome of filament uncoupling by twisting. At field below B_p, uncoupling leads to a higher loss, which is inevitable but not an issue for high field applications where the imposed field always exceeds B_p of the

filaments/sub-wires. As shown in Fig. 5, the loss factor of twisted wire of L_p=12 mm at different temperatures (inset of Fig. 5) can be collapsed into a common one as $\Gamma(\beta)$ in a wide vicinity of B_p (0.1<β<10), confirming its origin of superconductor hysteresis.
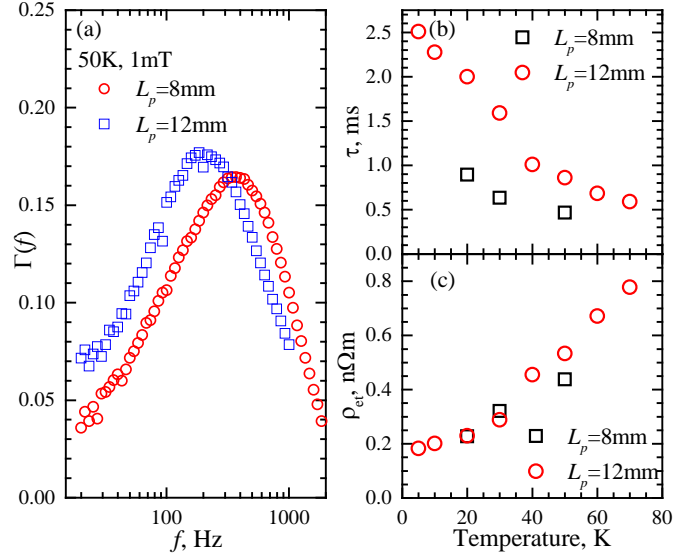

Fig. 6. For wires with different twist pitches of 8 mm and 12 mm, (a) loss factor as a function of field frequency f, together with (b) time constant and (c) transverse resistivity at different temperatures.

C. Coupling Current Losses and Time Constant

At sufficiently small fields, coupling current loss becomes evident as Q slows from B_0^{3+} towards B_0^2, which corresponds to a constant loss factor as found in the Fig. 4 inset and in Fig. 5. The dominance of the coupling current loss extends to higher field at lower temperatures with increasing B_p. Note that the coupling current loss does not scale with β for different temperatures. Instead, the losses reduce with increasing temperature at 19 Hz.

The loss factor of coupling current among the twisted filaments is given by [8]:

$$\Gamma_{CP}(z) = \lambda_f \frac{\pi z}{z^2+1} \text{ and } z = 2\pi f \tau_f$$

$$\tau_f = \lambda_f \frac{\mu_0}{2\rho_{et}} \left(\frac{L}{2\pi}\right)^2 \tag{2}$$

where $\lambda_f < 1$ is the effective internal flux fill factor which takes into account the diamagnetic contribution from the filaments, and τ_f is the effective time constant of the coupling current. As a function of frequency, Γ_{CP} reaches a peak value of $\frac{1}{2}\pi\lambda_f$ at $2\pi f \tau_f = 1$. Fig. 6(a) indicates $\Gamma_{CP,max}$~0.17 hence λ_f ~ 0.1. The peak frequencies are 390 Hz and 185 Hz for L_p = 8 mm and 12 mm respectively. Note that the ratio of the peak frequency is close to the expected 2.25 by the L_p^2 dependence.

It is encouraging that the time constant τ_f, shown in Fig. 6(b) for the two wires of different pitch, is in the millisecond regime. The increase of τ_f, with reducing temperature is the result of lower matrix resistivity. Equation (2) highlights the low flux fill factor as the ingredient for the short time constant, especially for a transverse resistivity ρ_{et} (Fig. 6(c)) almost as low as that of pure Ag at at a Residual
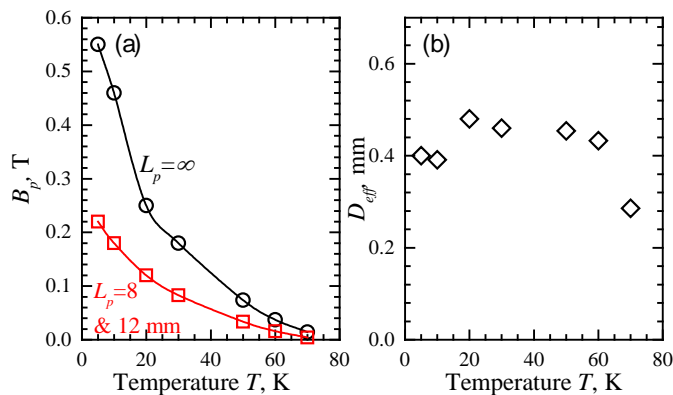
Resistance Ratio RRR=100.

Fig. 7. (a) Full penetration field of twisted ($B_{p,Lp}$, with L_p = 8 mm and 12 mm) and non-twisted ($B_{p,\infty}$) at different temperatures and (b) deduced effective diameter of coupling.

D. Effective Diameter of Decoupling

Similar to the non-twisted wire, the full penetration field B_p of twisted wires can be determined either directly at $T \geq 20$ K using the peak position of $\Gamma(B_0)$ or indirectly by achieving a common $\Gamma(\beta)$ scaling. The results are shown in Fig. 7(a) together with $B_p(T)$ of the non-twisted wire. Assuming no J_C degradation due to twisting, the effective diameter of coupling is $D_{eff} = B_{p,Lp}/B_{p,\infty} \sim 0.4$ mm $\sim 1.6 D_{sw}$, as shown in Fig. 7b. Such an effective diameter of coupling seems to suggest a partial of coupling of neighbouring sub-wires.

IV. CONCLUSION

AC loss measurements at a wide range of temperatures (5 K – 70 K) with sweeping the amplitude and frequency of ac sinusoidal field have revealed rich details of the hysteresis and coupling current losses. The twisted conductors showed classical behavior of uncoupling by filament twisting, although some partial coupling among adjacent sub-wires still existed with the effective coupling diameter of 60% larger than the sub-wire diameter.

The coupling current loss was rather low, primarily due to a small flux fill factor λ_f of just 10%. The same mechanism also led to a promising short time constant for the coupling current, even with the transverse resistive matrix behaving like pure silver. Hence a low contact resistance between the filaments and the matrix was also implied. It should be noted that the small flux fill factor could change in high external field and with wire architecture. It is an important aspect for future studies.

The standard expressions for the critical coupling length and the time constant of the coupling current seemed to hold well and the simple sum of coupling current and hysteresis losses appeared to work satisfactorily. However the penetration loss was not observed. It might be the result of partial coupling among the adjacent sub-wires and should be an important topic for further investigation due to its importance in the fully penetrated regime.

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