# Macroscopic Magnetic Coupling Effect: The Physical Origination of HTS Flux Pump

Wei Wang[1,*] and Tim Coombs[2]

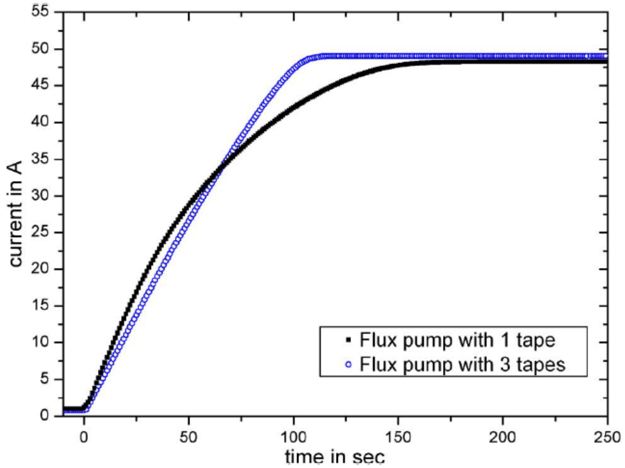
[1]Sichuan University, People's Republic of China

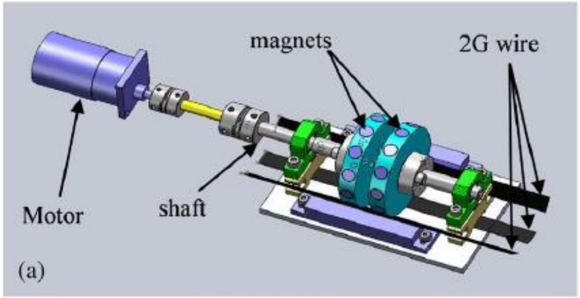
[2]University of Cambridge, United Kingdom

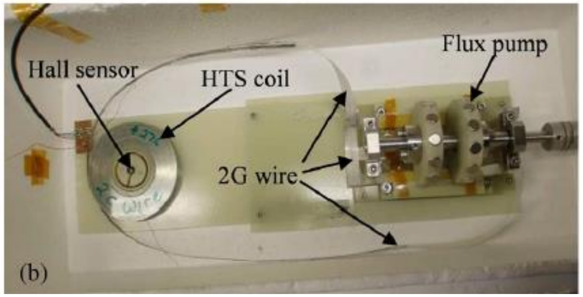
# HTS flux pump – rotating magnet disk

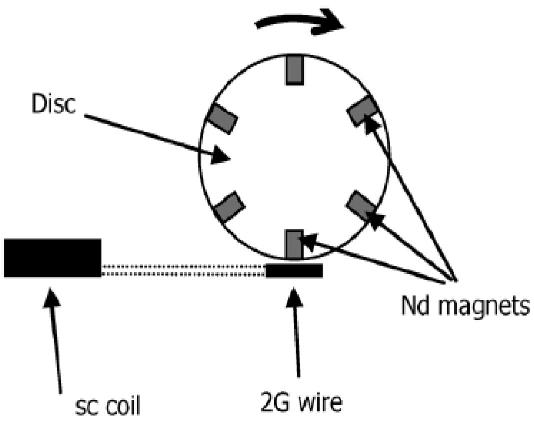
In the MT conference in 2011, C. Hoffman had displayed an HTS dynamo which pumps magnetic flux into an HTS closed-loop.

Traits: rotating magnet disk



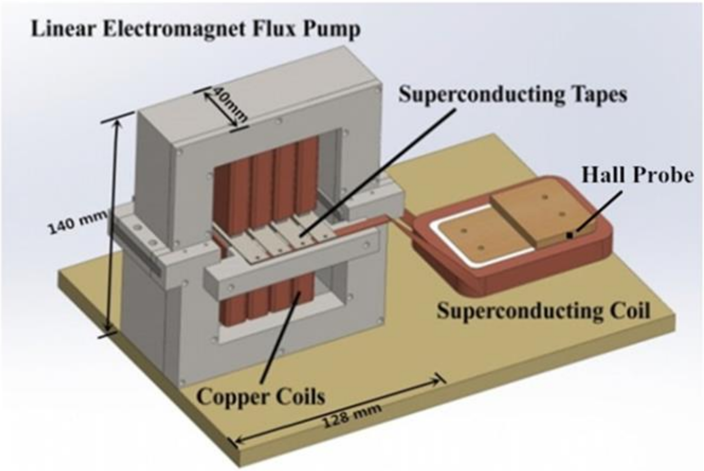



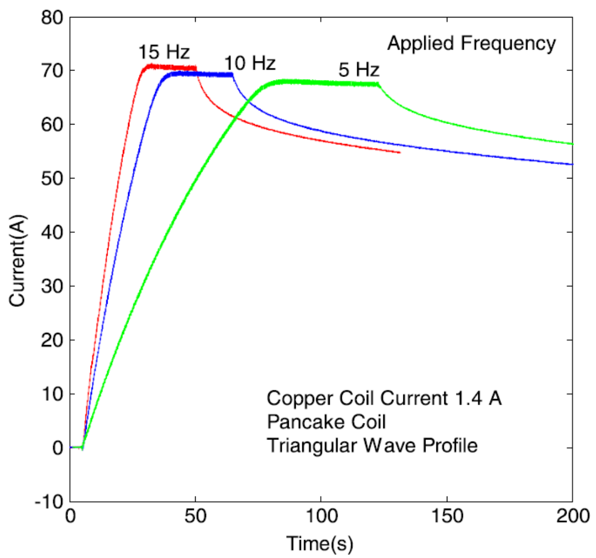

*Courtesy of C. Hoffman*
*IEEE T Appl Supercond 21, 1628(2011)*

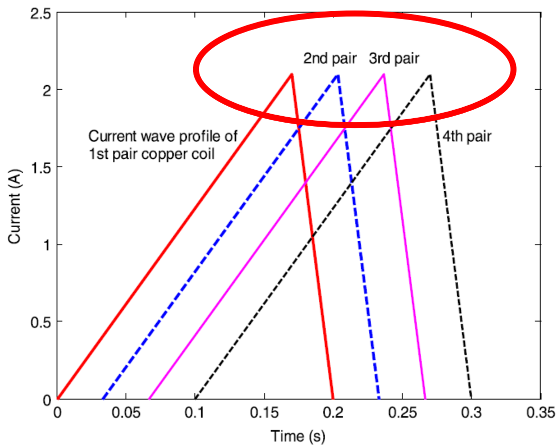
# HTS flux pump – linear pulse coils

Second method was achieved by Z.Bai and L.Fu, using linearly arranged coils which was pulse-charged in sequence.

Traits: linear pulse coils



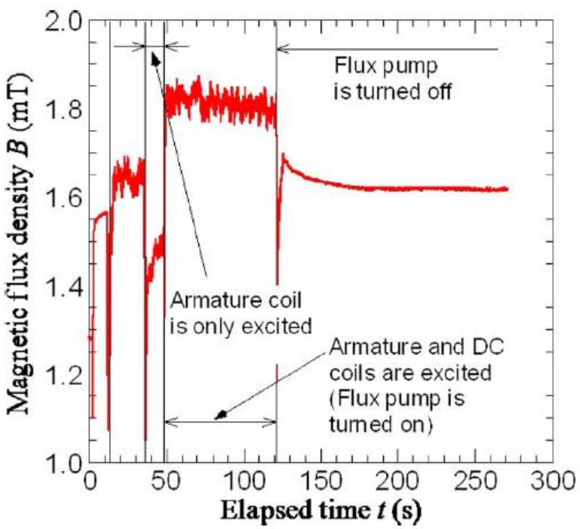



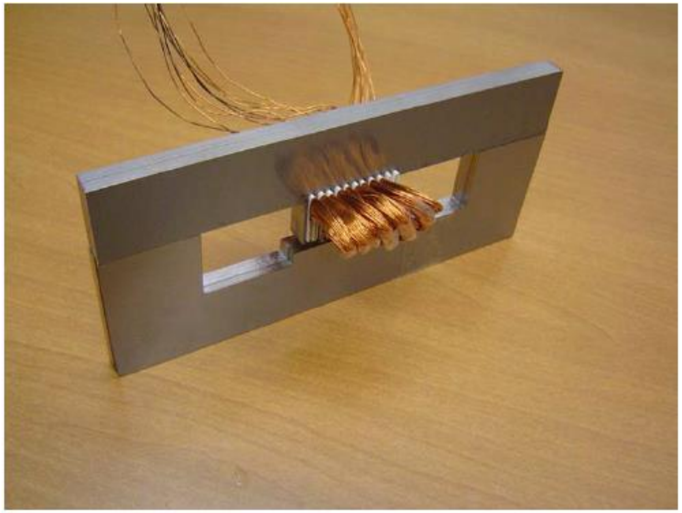

*Courtesy of L.Fu*
*IEEE T Appl Supercond 25, 4603804 (2015)*

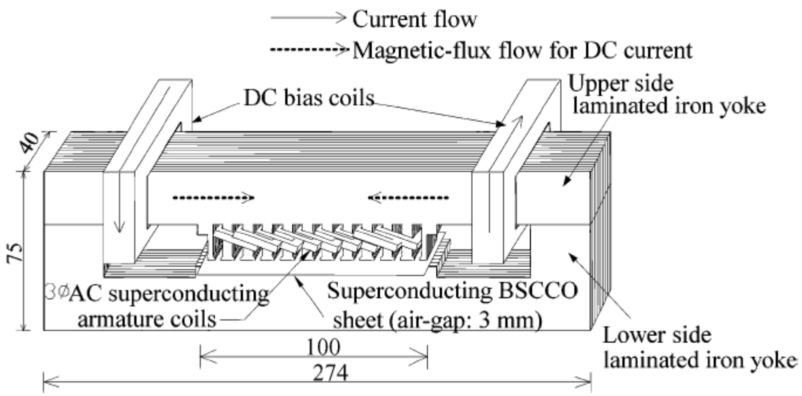
# HTS flux pump – linear motor stator

Third method was achieved by Y.Chung and N. Amemiya, using linear motor stator to generate travelling wave.

Traits: linear motor stator



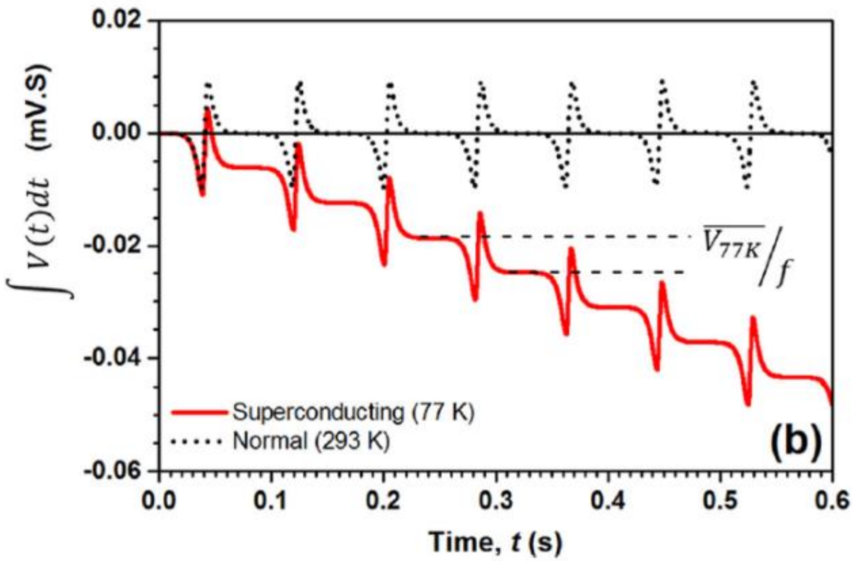



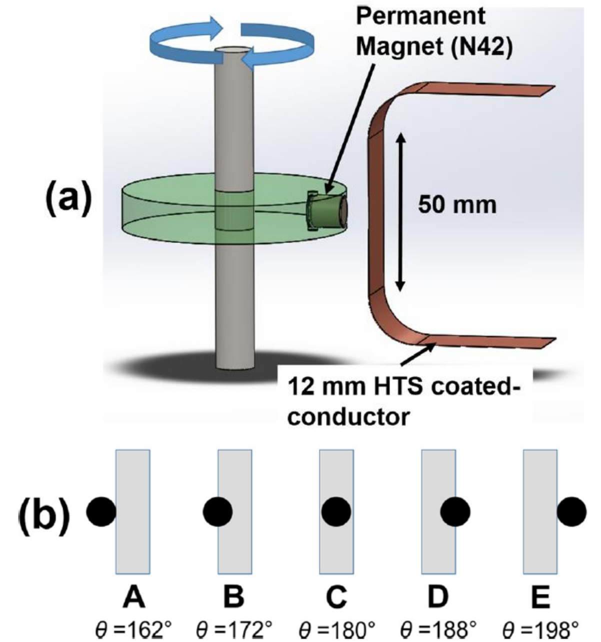


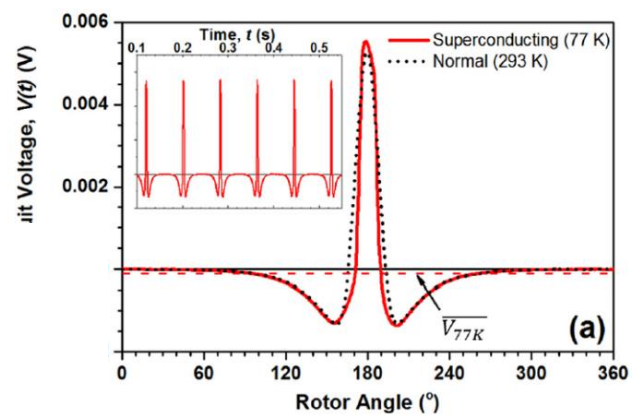

*Courtesy of N.Amemiya*
*IEEE T Appl Supercond 20, 3, 1033(2010)*

# Measurement of the inductive superconducting dc voltage

Z.Jiang and C.W.Bumby had measured the dc output voltage on the terminals of the superconducting stator, induced by the rotating magnet. “Dynamics resistance” was proposed to explain the phenomenon.




*Courtesy of Jiang and Bumby*
*Appl Phys Lett, 105,112601,2014;*
*Appl Phys Lett, 108,122601,2016*

# What is the origination of the inductive dc voltage?

Based on Faraday's Law of Induction:

**AC magnetic field induces AC electromotive forces, other than DC.**

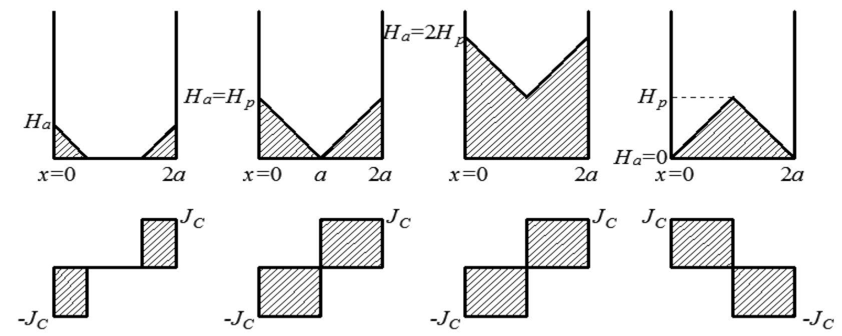
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$emf = -\frac{d\Phi}{dt}$$

Based on classic Bean's critical state model:

**AC magnetic field causes zero flux flow from one side to other, should have no DC output.**

**(a) Zero-field cooling**



# How to reveal the mystery of HTS flux pump?

Common traits in all types of HTS flux pump (rotating magnet, pulse type, linear motor type):

1. Using ac travelling wave instead of homogeneously oscillating field, in other words, there are magnetic poles and fields are **strongly inhomogeneous** in space.

2. Using HTS film instead of HTS bulk.

As we can hardly find answer from macroscopic theories, we decided to:

1. Find answer from microscopic vortex dynamics

   Reason: macroscopic electromagnetic theories for type-II superconductor are built on collective vortex behaviours.

2. Return to classic model (Bean model)'s geometry: long rod and wide slab

   Reason: easy for comparative study with classic model.

# Clue 1: the vortex-vortex coupling

I.Giaever had uncovered a vortex-vortex coupling phenomenon in dual superconducting layers structure (**DC transformer**) which were electrically insulated.

Two cases coupling effect vanishes:

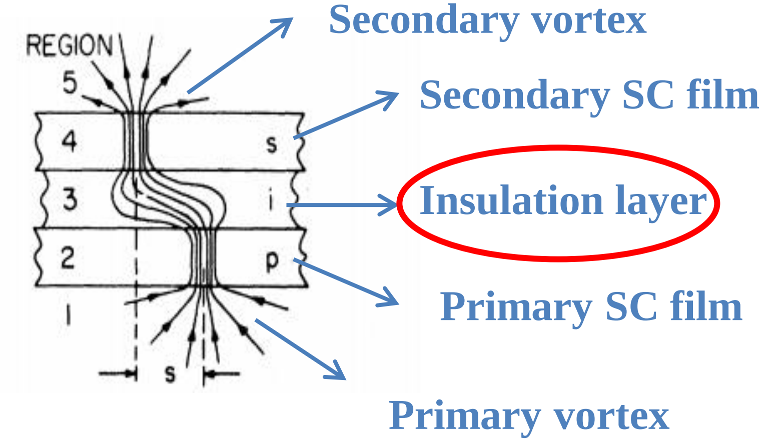
(1) The insulation layer is too thick: field smooth out;

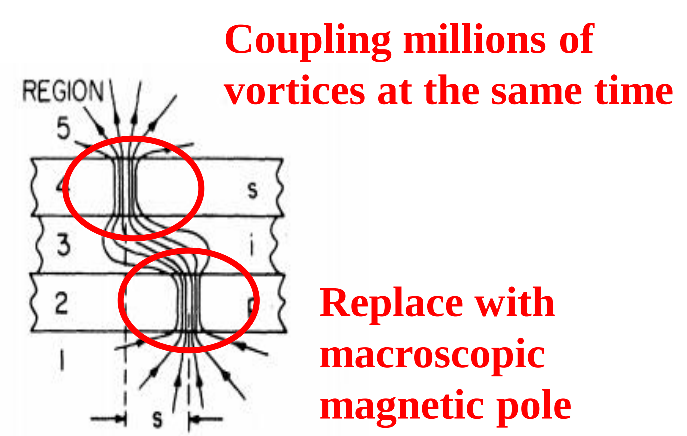
(2) The vortex density is too high: field smooth out.

**The coupling energy comes from the field inhomogeneity of the vortex structure.**

**Question 1: can vortex coupling effect be found in macroscopic scale?**

Coupling between a magnetic pole and millions of vortices at the same time?



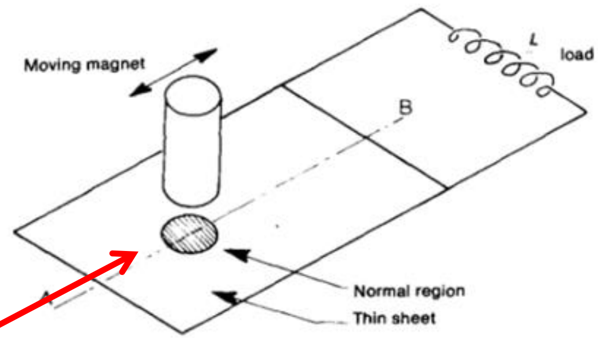




*Courtesy of I.Giaever and J.R.Clem*
*Phys Rev Lett, 15,825,1965, Phys Rev B, 9,898,1974*

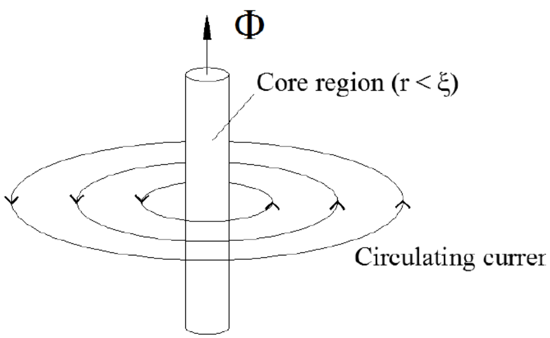
# Clue 2: the LTS flux pump

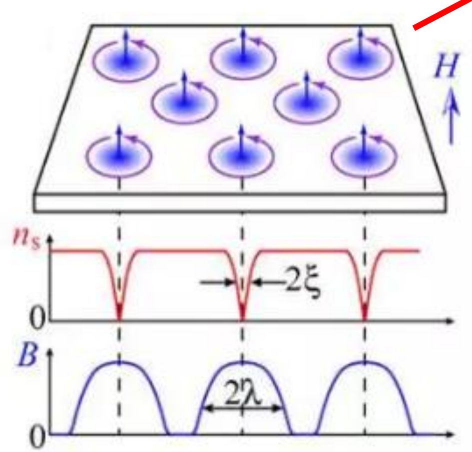
LTS flux pump was achieved by partially normalize a superconducting film by strong field or heating, however, which is inapplicable for HTS film.

**Question 2: can HTS flux pump been realized by vortex dynamics instead of partially normalize the film?**

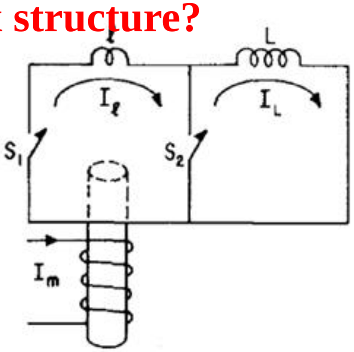



**Normal region within the coherence length ξ**




**Replace the normal spot with a vortex structure?**




**Magnetic quantum**

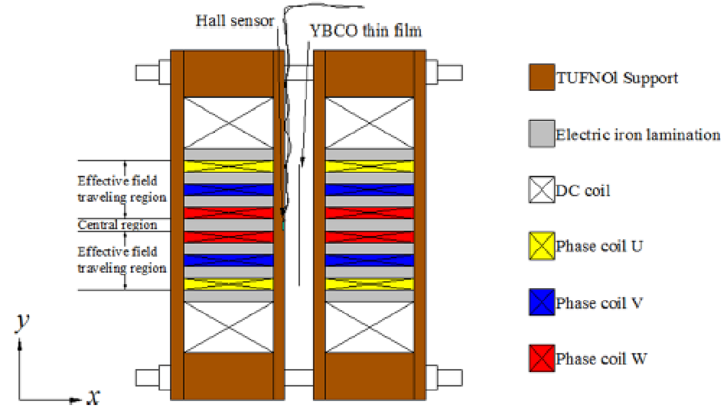
$\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Wb

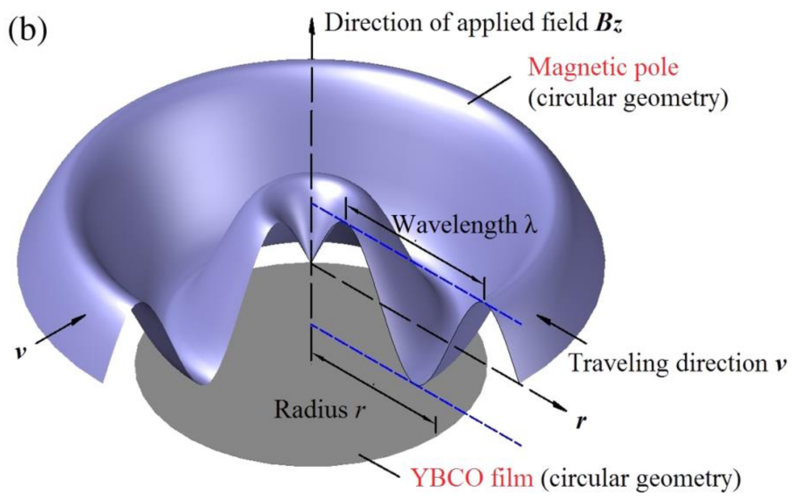
*Courtesy of Klundert Cryogenics, 21,195,1981*

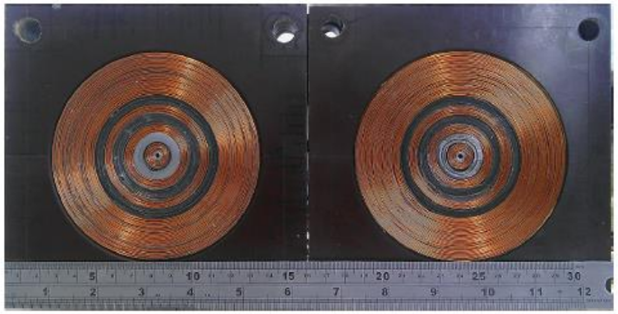
# The CTMFP: the experimental setup

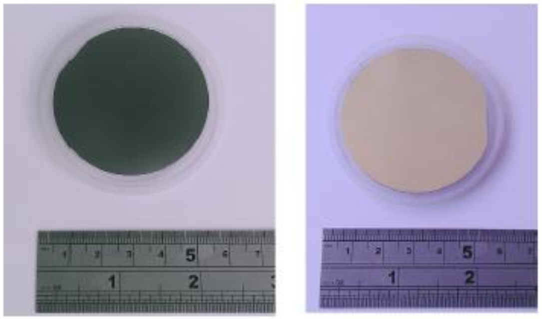
The circular-type magnetic flux pump (CTMFP) device generates circular-shape travelling magnetic poles, to magnetize a circular-shape YBCO film. This geometry is easier for comparative study with Bean's model.

Comprised of: three phase ac windings and dc windings.




(a) (b)

*W.Wang and T.Coombs*
*J Appl Phys, 113,213906,2013*

SICHUAN UNIVERSITY

UNIVERSITY OF CAMBRIDGE

JOURNAL OF APPLIED PHYSICS 113, 213906 (2013)

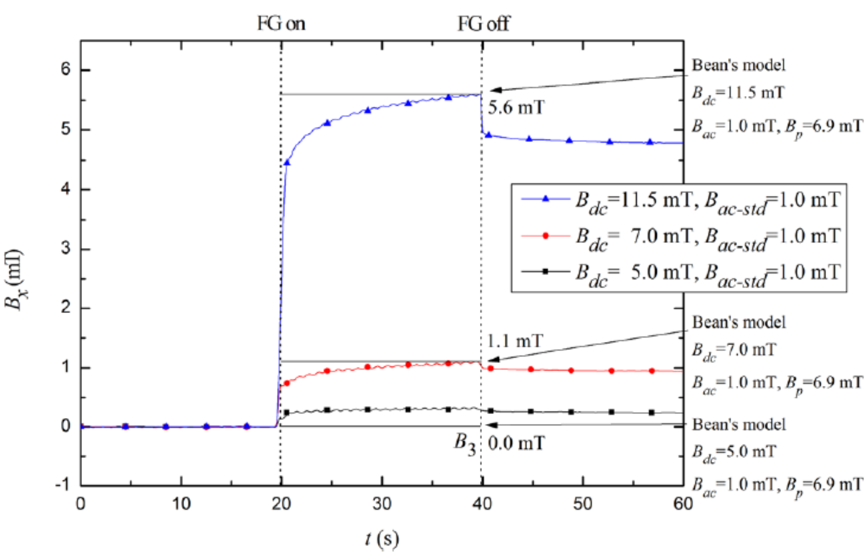
# Vortex migration caused by travelling magnetic wave in a 2 in. diameter $YBa_2Cu_3O_{7-\delta}$ thin film

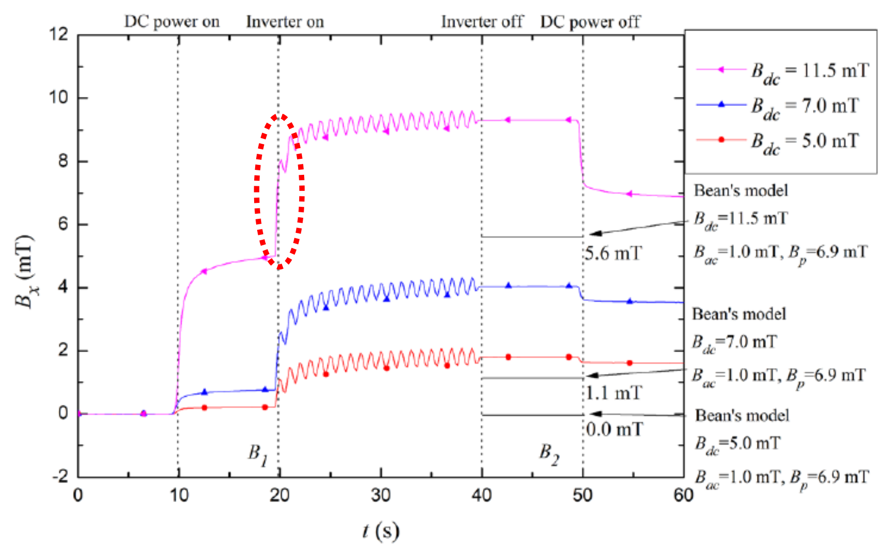
W. Wang[a)] and T. A. Coombs
*Electric Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, United Kingdom*

In the case of the same amplitude:

(1) In homogeneous oscillating field: magnetization fits the Bean's model prediction;

(2) In AC travelling wave: there is a jump of magnetic flux in the center, which doesn't fit the Bean's model prediction.



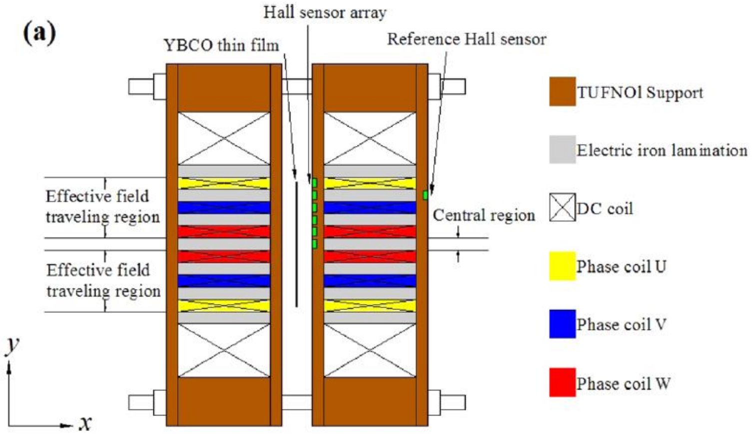
# CTMFP device: the FEM models

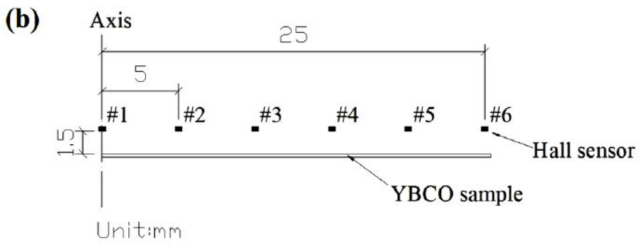
Finite-element method (FEM) model are based on **H-formulation and E-J power relationship**, which was built on an **axial-symmetric geometry** in COMSOL.

$$\begin{pmatrix} -\frac{\partial^2 H_r}{\partial z^2}+\frac{\partial^2 H_z}{\partial r \partial z} \\ \frac{1}{r}\frac{\partial}{\partial r}\left[r\rho\left(\frac{\partial H_r}{\partial z}-\frac{\partial H_z}{\partial r}\right)\right] \end{pmatrix} = -\mu_0\mu_r \begin{pmatrix} \frac{\partial H_r}{\partial t} \\ \frac{\partial H_z}{\partial t} \end{pmatrix}$$

Experiments are also conducted to measure the magnetic flux density along the radius.

$$E = E_C\left(\frac{J}{J_C}\right)^n$$




**Six Hall sensors to measure the dynamic magnetic profile.**

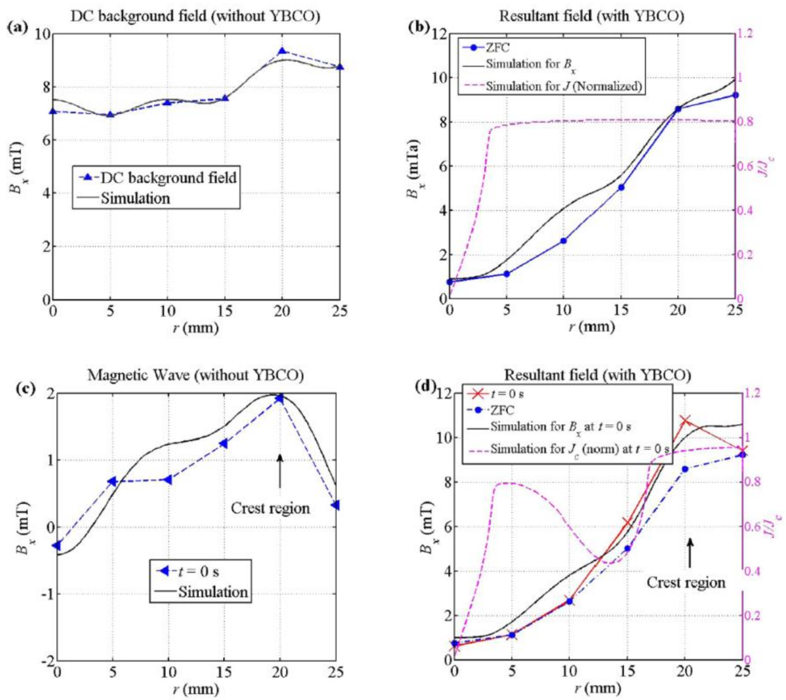
*W.Wang and T.Coombs*
*Appl Phys Lett, 104,032602,2014*

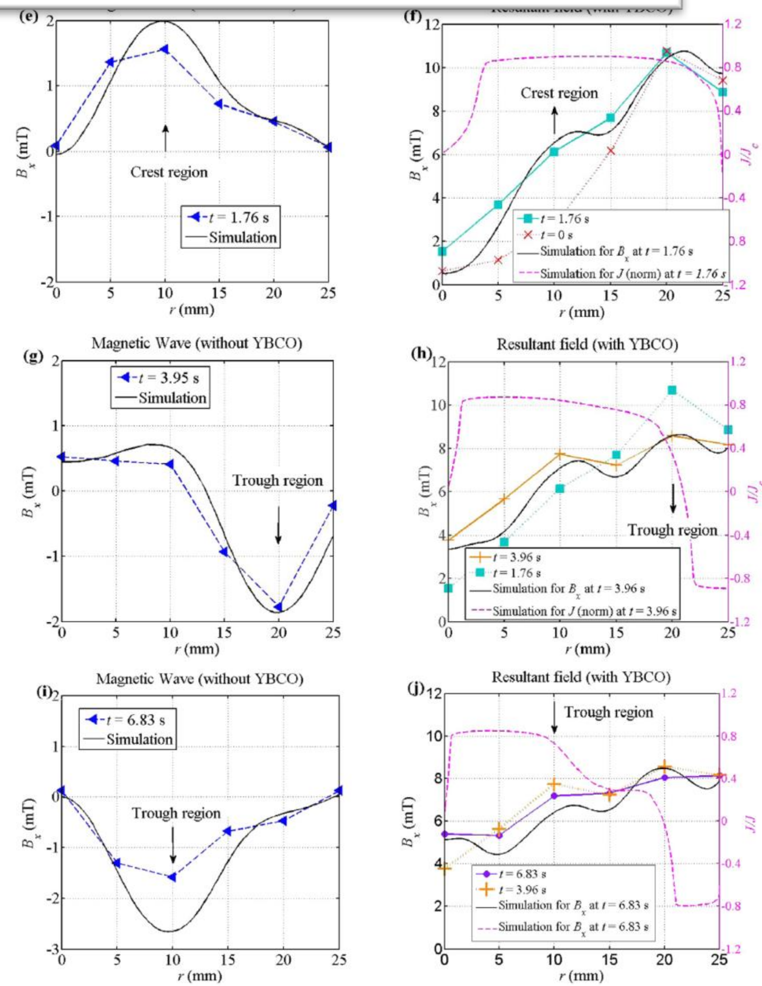
APPLIED PHYSICS LETTERS 104, 032602 (2014)

# Direct measurement of the vortex migration caused by traveling magnetic wave

Wei Wang (王为),[a)] Fred Spaven, Min Zhang, Mehdi Baghdadi, and Timothy Coombs
*Electric Engineering Division, Department of Engineering, University of Cambridge, Cambridge, United Kingdom*

**The magnetization based on ac travelling wave can be accurately reproduced by the FEM models to reveal the internal flux motion and current distribution.**



APPLIED PHYSICS LETTERS **104**, 032602 (2014)

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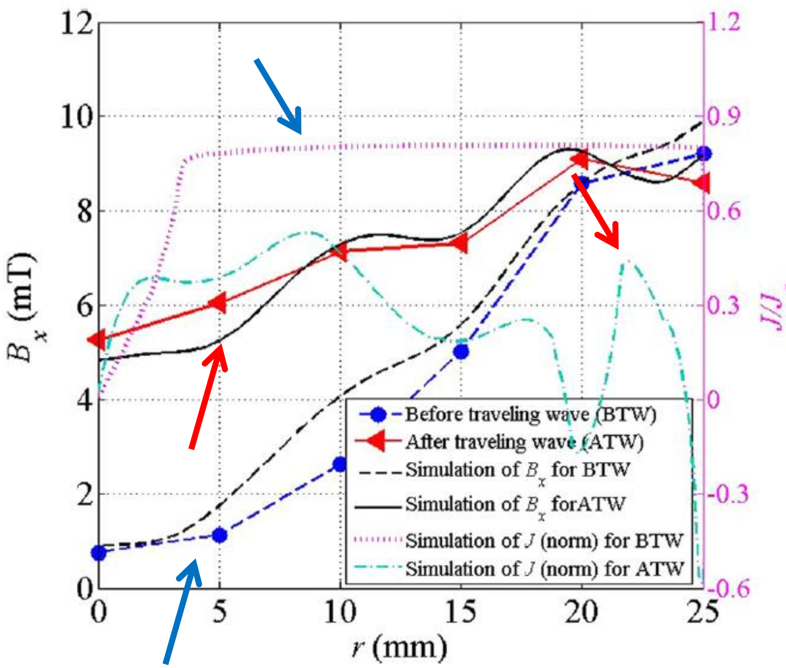



Magnetization results:

1. In case of homogeneous magnetic field:

   Magnetization fits the Bean's model with critical values of both the magnetic gradient and current density.

2. In case of AC travelling wave:

   Magnetization doesn't fit the Bean's model with **intermediate values** of the current densities (smaller than the critical value).

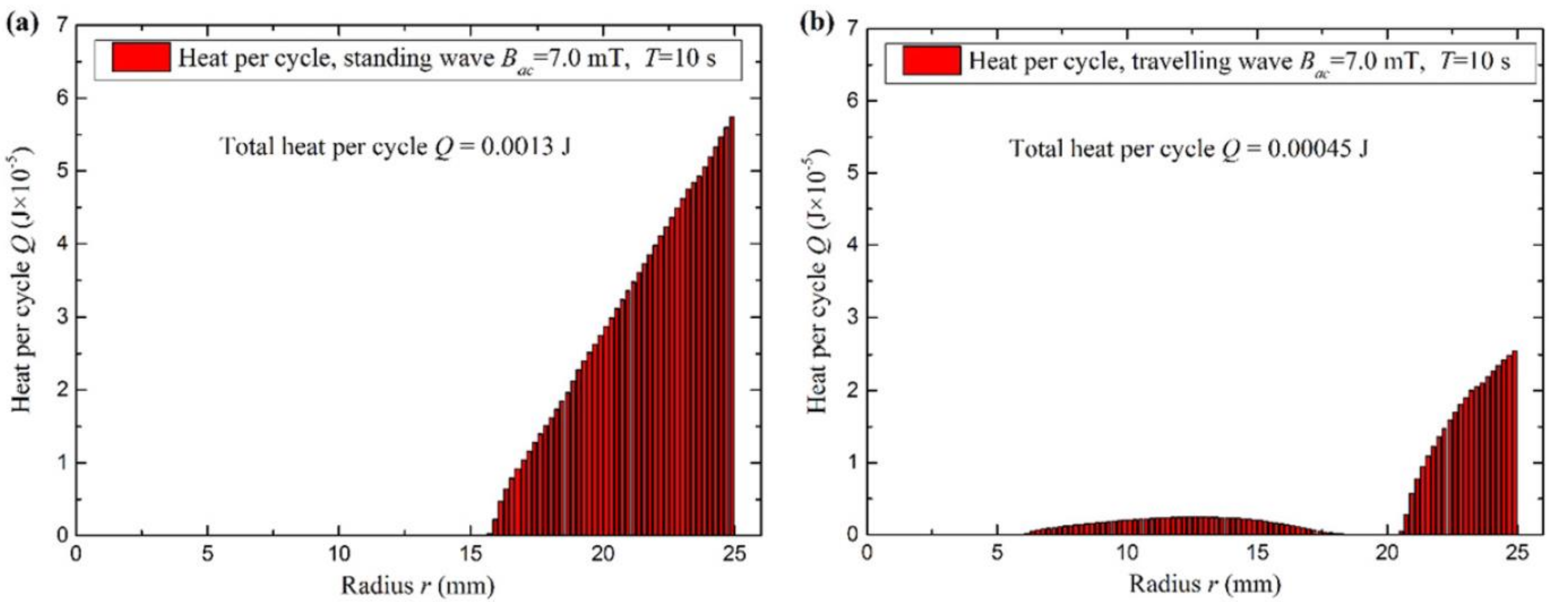
*W.Wang and T.Coombs*
*Appl Phys Lett, 104,032602,2014*

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. 28 (2015) 055003 (10pp) doi:10.1088/0953-2048/28/5/055003

# The magnetisation profiles and ac magnetisation losses in a single layer YBCO thin film caused by travelling magnetic field waves

Wei Wang and Timothy Coombs

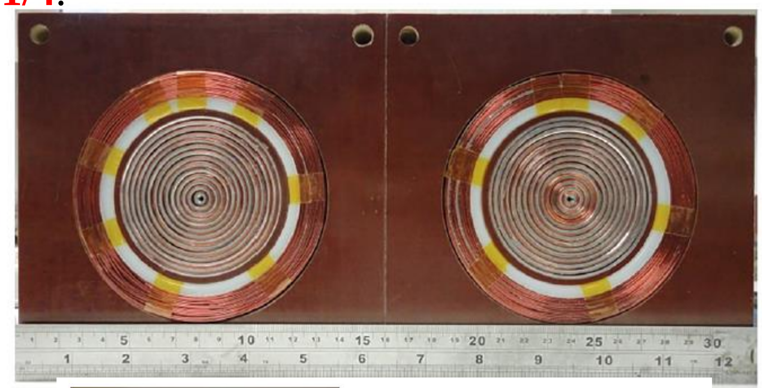
The amount of AC losses and distributions in AC travelling wave is also very different from homogeneous field condition.

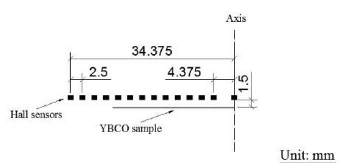


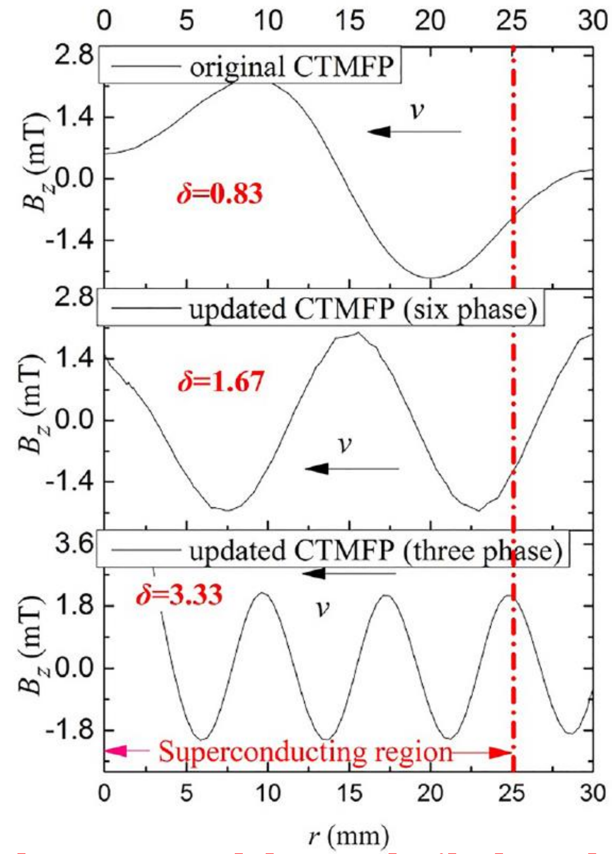

*W.Wang and T.Coombs*
*Supercond Sci & Technol, 28,055003,2015*

# The updated CTMFP device: Shortening the wavelengths

With the updated CTMFP device, **the wavelength of the AC travelling wave was shortened to 1/2 and 1/4**.






*W.Wang and T.Coombs*
*Appl Phys Lett, 110,072601,2017*

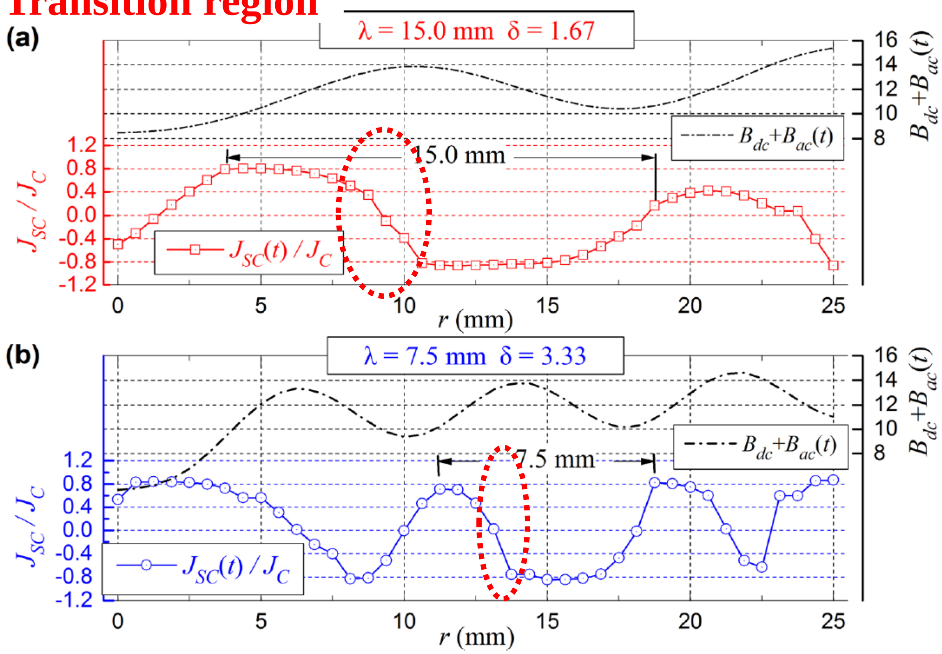
**Updated FEM model was built based on H-formulation and E-J power law, and was verified by the experimental results.**

APPLIED PHYSICS LETTERS 110, 072601 (2017)

# Magnetization of YBCO film with ac travelling magnetic waves of relatively short wavelengths

Wei Wang[1,a)] and Tim Coombs[2]
[1]*School of Electrical Engineering and Information, Sichuan University, Chengdu 610065, China*
[2]*Electrical Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, United Kingdom*

**Transition region**




**Transition region**

An updated FEM model was built to reveal the internal flux motion and current distribution, it was found that:

The current distribution is wavelike, with critical values near the pole region, intermediate values between the poles, which can be demonstrated as:

+Jc -> -Jc -> +Jc

while -> is the transition region, with smaller value than the critical value.

**The existence of transition regions and wavelike current distribution explains the diminished magnetic gradient.**

*W.Wang and T.Coombs*
*Appl Phys Lett, 110,072601,2017*

SICHUAN UNIVERSITY 四川大學 UNIVERSITY OF CAMBRIDGE

# The updated CTMFP device: uncover the macroscopic magnetic coupling effect

**<u>Target: reveal whether magnetic coupling exists in macroscopic scale?</u>**

Magnetic coupling originate from field inhomogeneity.

For an AC travelling wave, the field inhomogenetiy is determined by two factors:

(1) Wavelength: shorter the wavelength, stronger the field inhomogeneity;

(2) Field amplitude: larger amplitude has stronger inhomogeneity.

**Case study: different wavelengths, the same amplitude.**

<u>Only the wavelength determines the field inhomogeneity.</u>

**Studying the internal flux motion induced by pure AC travelling wave.**

<u>Tool: with the verified FEM model</u>

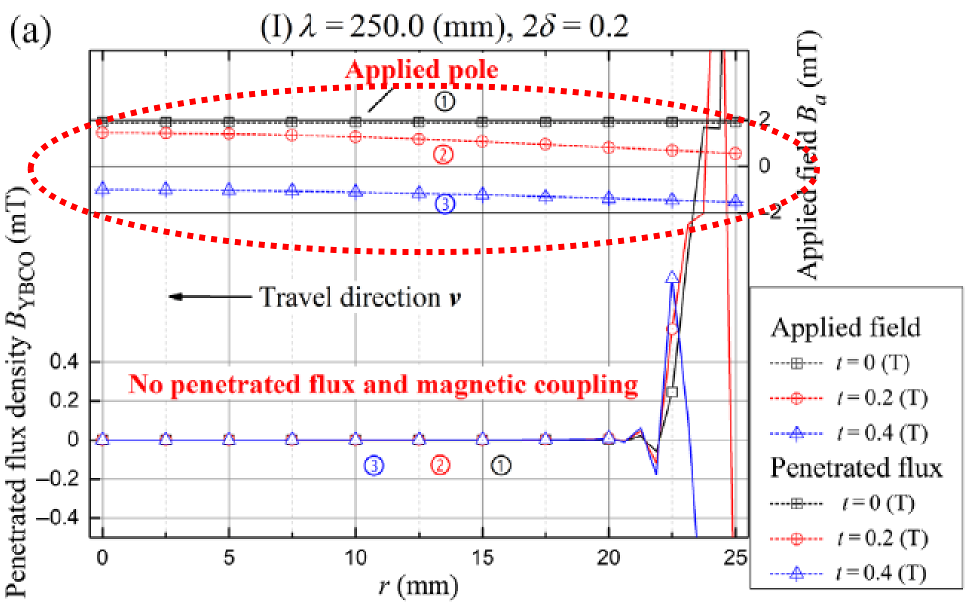
PHYSICAL REVIEW APPLIED **9**, 044022 (2018)

**Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump**

Wei Wang[1,*] and Tim Coombs[2]

Case 1: relatively large wavelength, almost homogeneous field

Magnetization fits Bean's model: field oscillates in the outer region, cannot penetrate into the central region, magnetic gradient equals critical value.




Wavelength: λ=250.0 mm

Pole(s) within the sample: 0.2

Applied amplitude: 2.0 mT

Penetration field in homogeneous field:

Bp=7.0 mT(Bean's model)

In long wavelength, magnetization fits the Bean's model prediction.

*W.Wang and T.Coombs*
*Phys Rev Appl, 9,044022,2018*

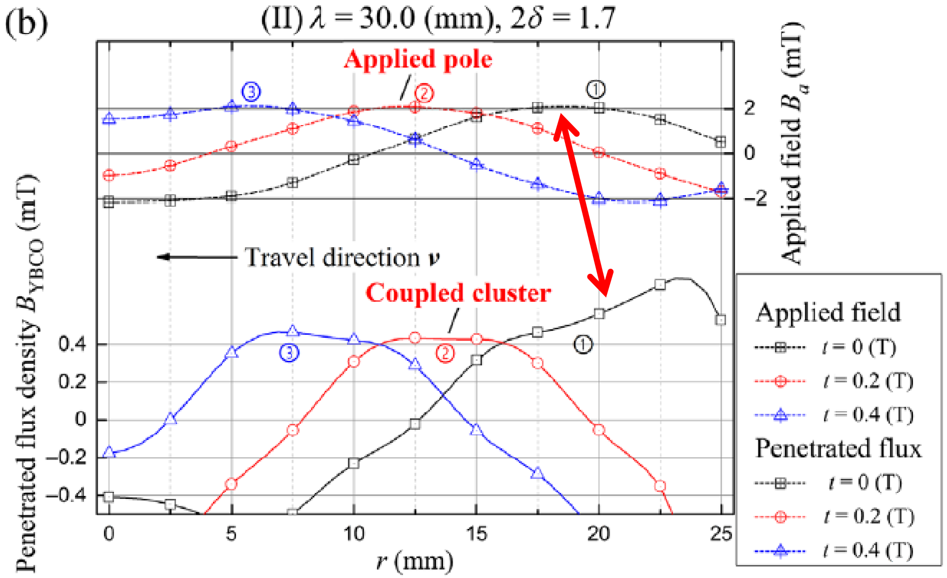
PHYSICAL REVIEW APPLIED **9**, 044022 (2018)

**Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump**

Wei Wang[1,*] and Tim Coombs[2]

Case 2: relatively small wavelength, inhomogeneous field

**Magnetic coupling effect was uncovered**, while a lump of magnetic flux was travelling with applied pole into the central region.




Wavelength: $\lambda$=30.0 mm

Pole(s) within the sample: 1.7

Applied amplitude: 2.0 mT

~~Penetration field in homogeneous field:~~

Bp=7.0 mT(Bean's model)

In relatively short wavelength, magnetic coupling effect was uncovered.

*W.Wang and T.Coombs*
*Phys Rev Appl, 9,044022,2018*

PHYSICAL REVIEW APPLIED 9, 044022 (2018)

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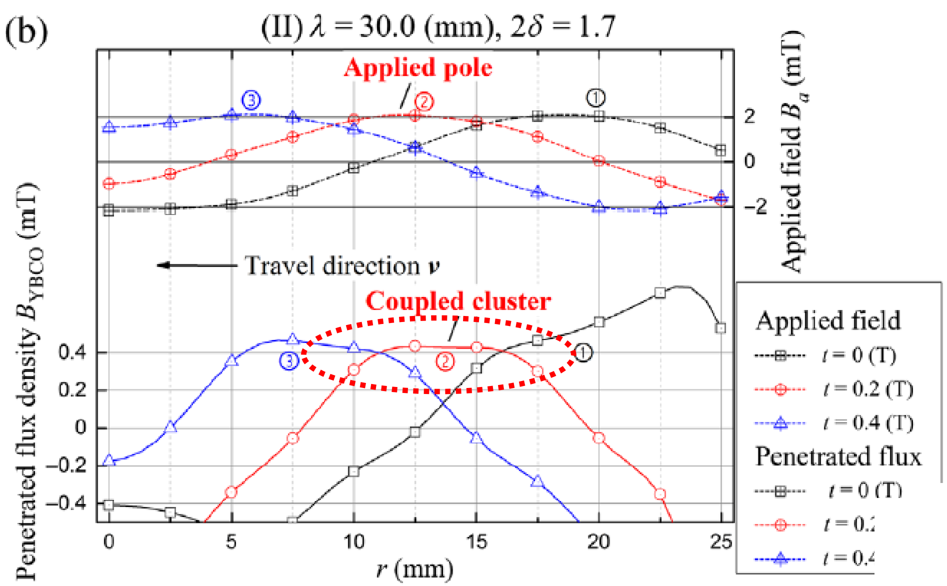
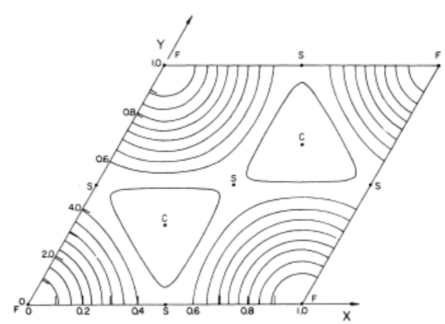



*W.Wang and T.Coombs*
*Phys Rev Appl, 9,044022,2018*

Other traits:

There are terrace region in the coupled flux, which resembles the "**terraced critical model**" (*Phy Rev Lett, 74, 2788, 1995*), which was induced by periodic pinning potential.

This suggests the AC travelling wave has introduced extra periodical pinning potential, **which fits theoretical prediction of "DC transformer"**(Clem, *Phys. Rev. B, 9, 898,1974*)



*Courtesy of Clem,*
*Phy Rev B, 9, 898, 1974*

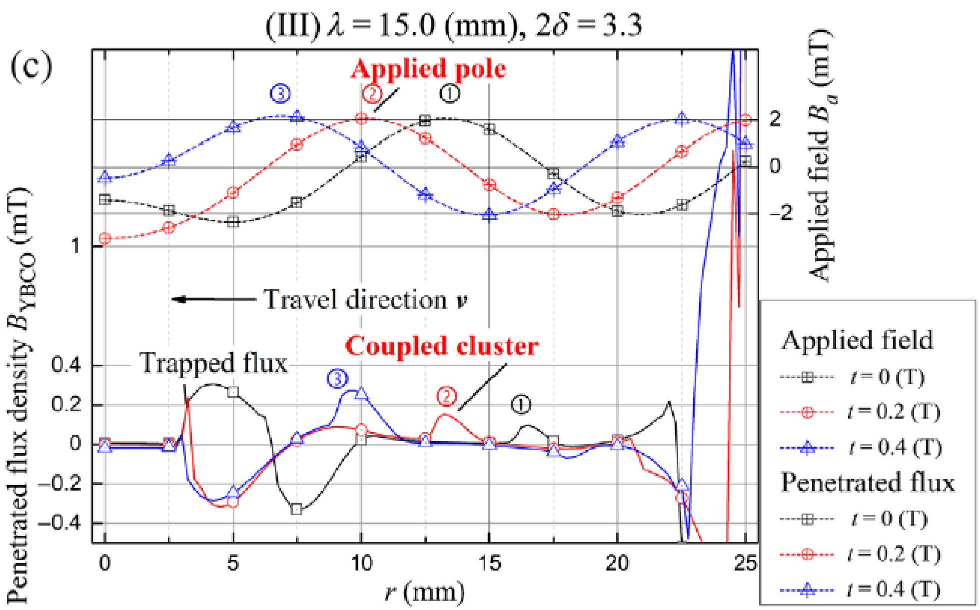
PHYSICAL REVIEW APPLIED **9**, 044022 (2018)

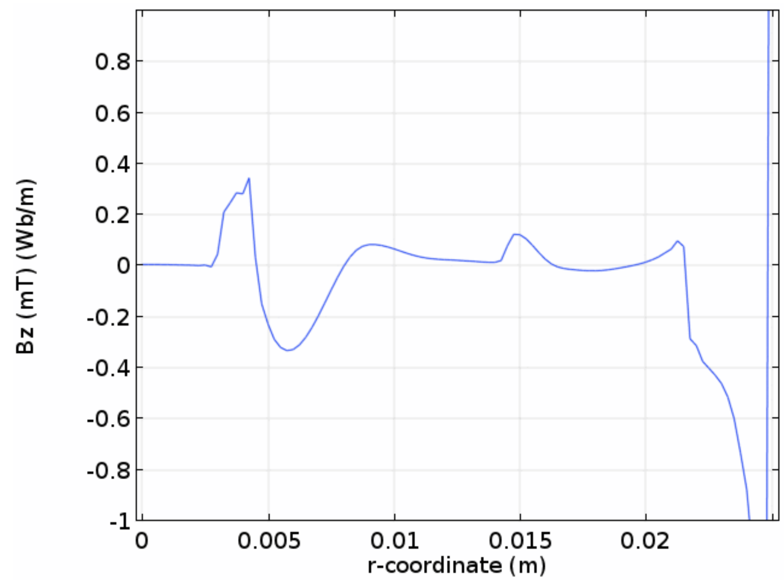
**Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump**

Wei Wang[1,*] and Tim Coombs[2]

Case 3: relatively very small wavelength, strong inhomogeneous field

**Strong magnetic coupling effect was observed**, while a lump of magnetic flux was travelling with applied pole into the central region.




*W.Wang and T.Coombs*
*Phys Rev Appl, 9,044022,2018*

Wavelength: λ=15.0 mm

Pole(s) within the sample: 3.3

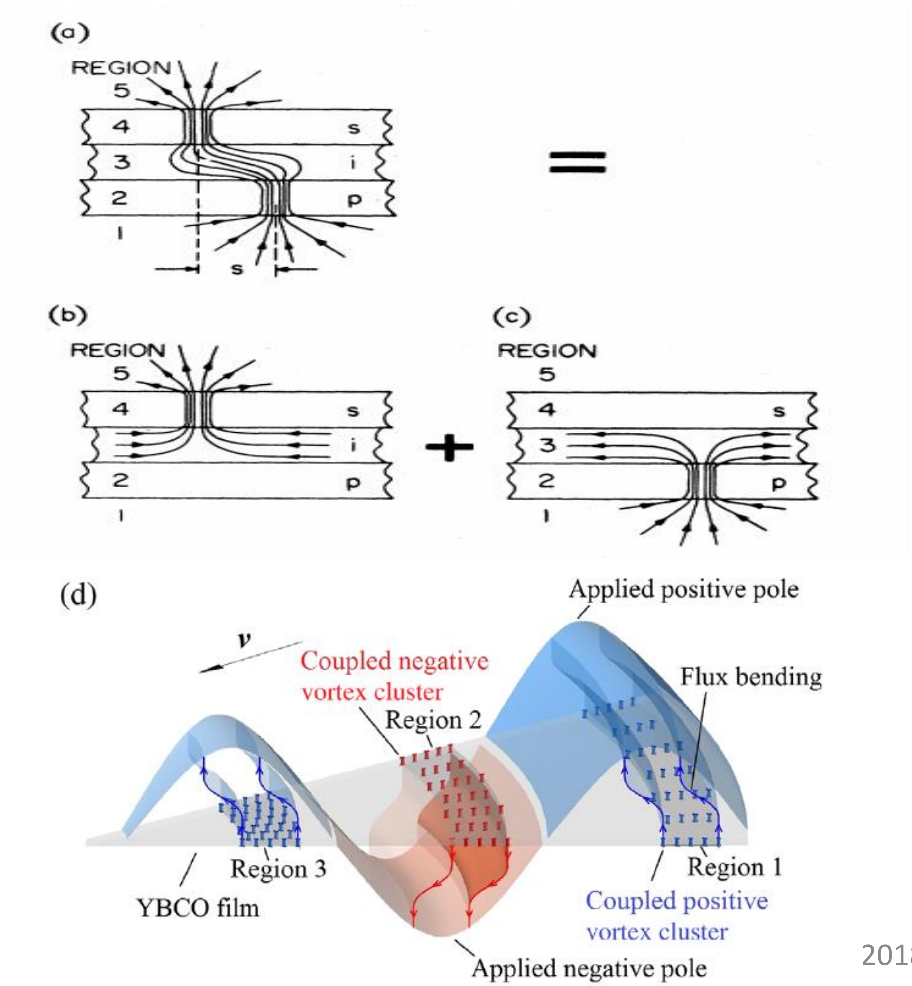
Strong magnetic coupling effect was observed.

PHYSICAL REVIEW APPLIED 9, 044022 (2018)

## Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump

Wei Wang[1,*] and Tim Coombs[2]

Case 3: relatively very small wavelength, strong inhomogeneous field




Traits:

1. Vortex cluster confined in isolated island, similar effect was observed in the superconducting – ferromagnetic bilayers (EPL,110(2015)37003; *Sci.Rep.*,*6*(2016)38557).
2. Ramping up of flux density, which can be explained by the circular geometry, suggesting strong magnetic coupling.
3. Misalignment between the applied pole and coupled cluster, which **fits the theoretically prediction that flux bending is the origination of the dragging force in DC transformer** (*Phys. Rev. B 12*,*1742*, *1975*).

**Superconducting magnetic coupling does exist in macroscopic scale.**

PHYSICAL REVIEW APPLIED **9**, 044022 (2018)

**Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump**

Wei Wang[1,*] and Tim Coombs[2]

HTS flux pump is explained by the macroscopic magnetic coupling effect:

Step 1: vortex cluster induced by the homopolar travelling wave;

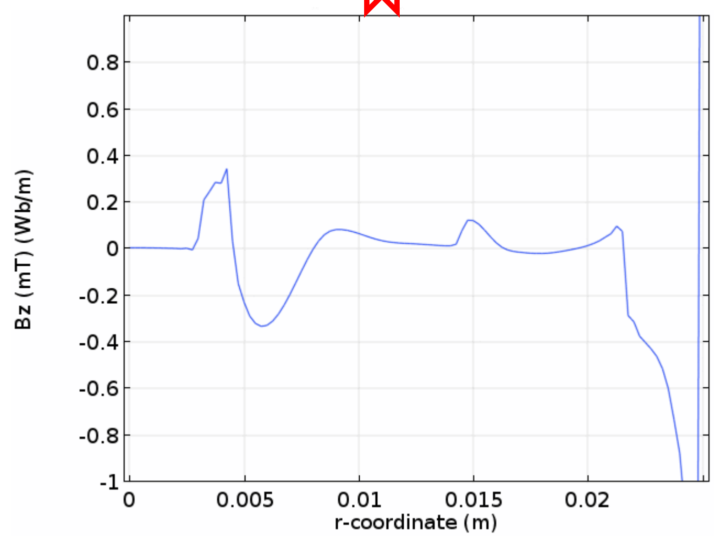
Step 2: coupling force drags vortex cluster across the YBCO film

Step 3: vortex cluster annihilates inside the closed loop, becoming trapped flux.

Step 4: No opposite vortices were induced or coupled in the nex half period due to DC biasing.

**Repeating above steps until a HTS closed-loop has been fully charged.**

**AC travelling has to be DC biased to avoid negative vortices induced and transported.**




*W.Wang and T.Coombs*
*Phys Rev Appl, 9,044022,2018*

PHYSICAL REVIEW APPLIED **9**, 044022 (2018)

## Macroscopic Magnetic Coupling Effect: The Physical Origination of a High-Temperature Superconducting Flux Pump

Wei Wang[1,*] and Tim Coombs[2]

Theoretically predictions for the HTS flux pump:

**(1)** **A pure ac traveling wave does not induce any trapped flux inside the HTS magnet**, as the transported positive vortices (first half period) cancel the negative vortices (second half period) during each period.

**(2)** **The magnetization of the HTS magnet can be reversed by reversing the dc bias field of the ac traveling wave**; as the polarization of the pole wave is reversed, then opposite vortices are coupled and transported into the HTS closed loop.

**(3)** **The magnetization of the HTS magnet can be reversed by reversing the propagating direction of the ac traveling wave**, as trapped vortices in the HTS closed loop are transported out.

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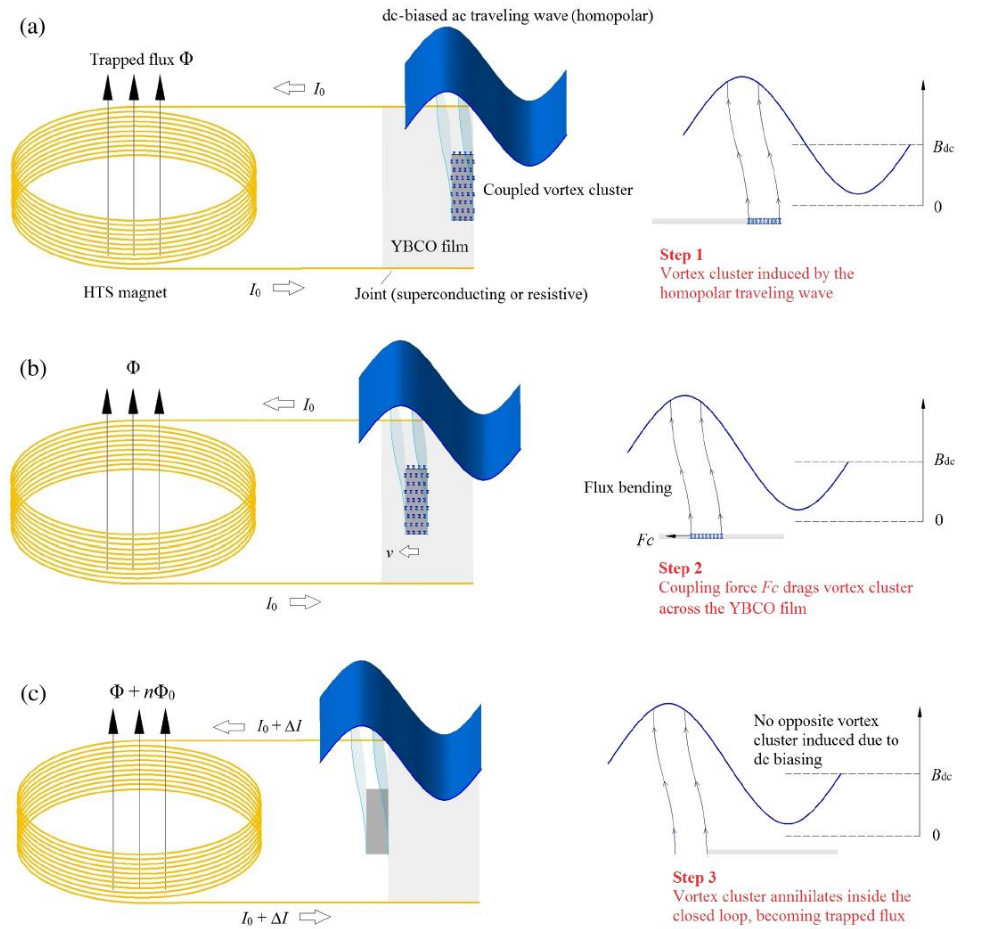

# Macroscopic magnetic coupling effect: the physical origination of HTS flux pump – verification by experiment

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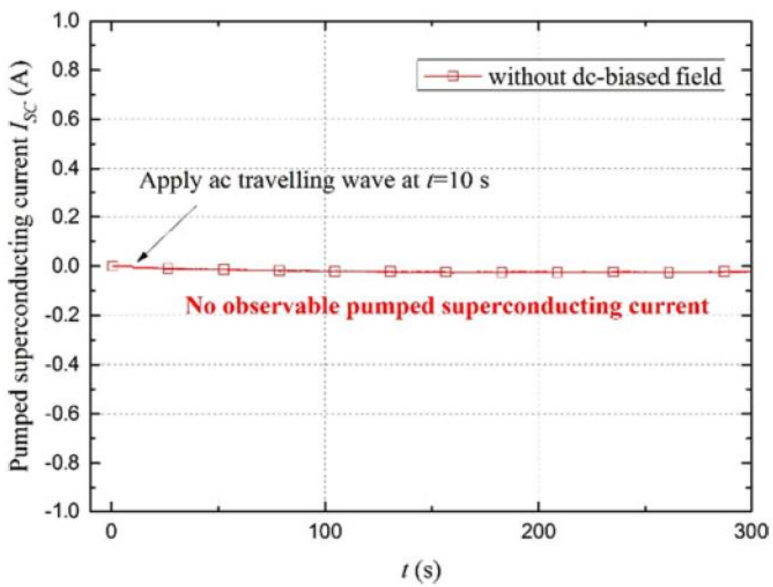


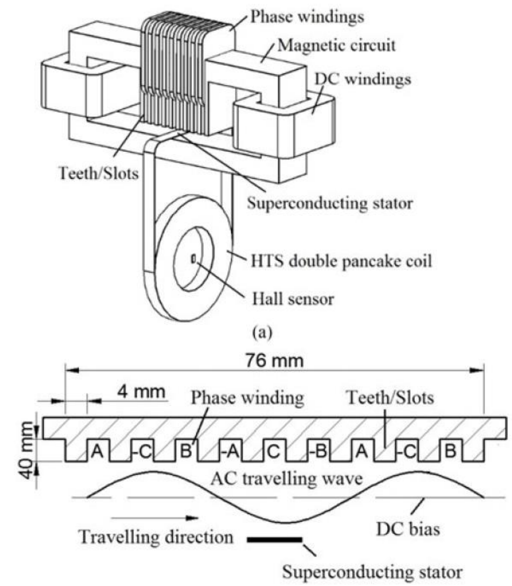


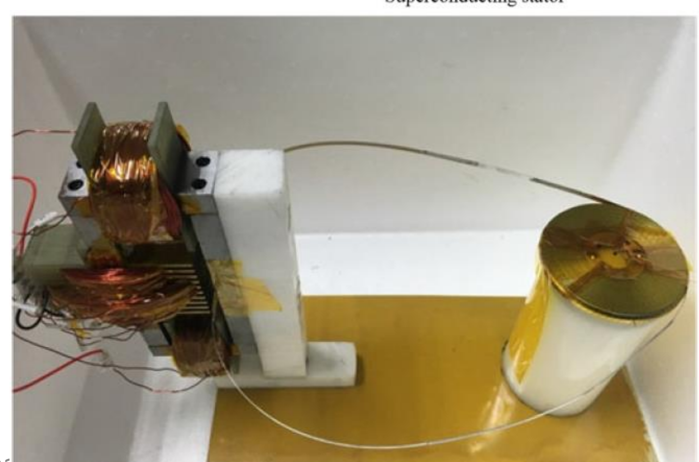

*W.Wang, et al,*
*IEEE Trans. Appl. Supercond. 28, 0600804 (2018).*

# Macroscopic magnetic coupling effect: the physical origination of HTS flux pump – verification by experiment

Theoretically predictions for the HTS flux pump:

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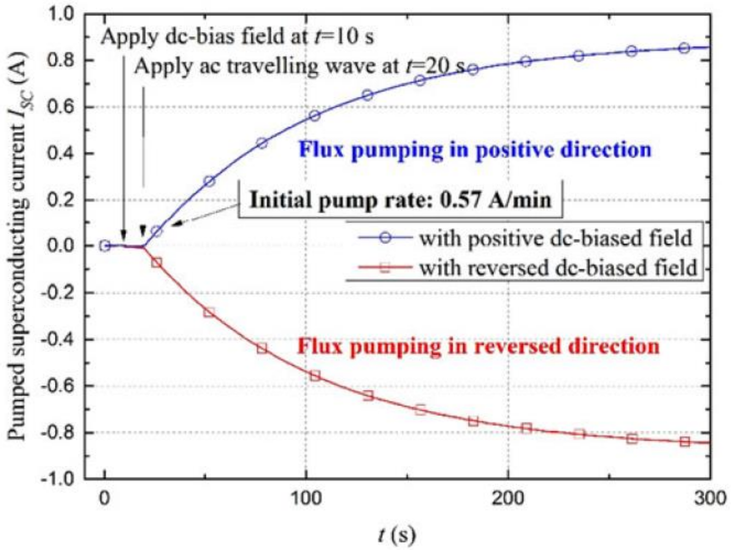


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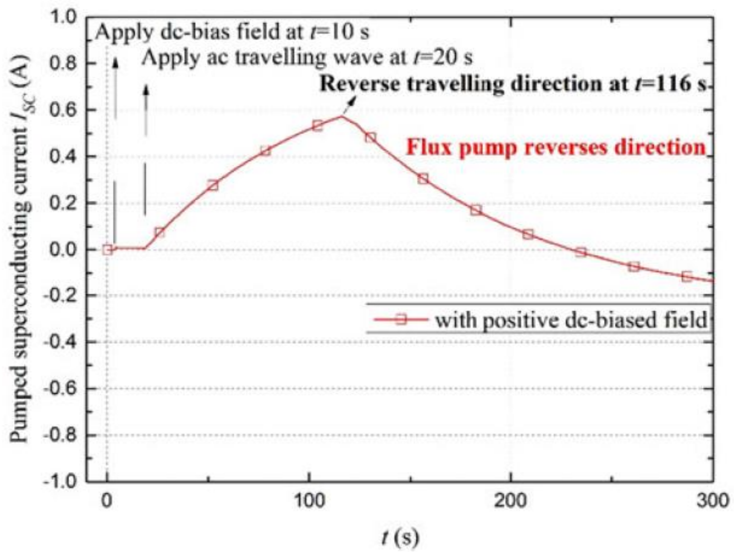


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**Experimental results fits and solidifies the theoretical predictions for HTS flux pump based on macroscopic magnetic coupling.**

# Conclusion

1. Magnetic coupling effect was uncovered in macroscopic scale, the coupling is between a magnetic pole and millions of superconducting vortices. In order to induce effective coupling, the wavelength must be short while field amplitude must be strong, i.e. the local field inhomogeneity is the crucial factor.

2. The physical origination of the HTS flux pump has been clearly answered by the macroscopic magnetic coupling effect. In order to transport neat magnetic flux into the close-loop, the AC travelling wave must be DC biased to eliminate coupling opposite vortices. Changing the travelling direction or the DC bias field can change the magnetization direction of the closed loop.

# Thank you very much for your time!

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