

Investigation on the Ultra-high Field Flux Pumped superconducting magnets

Chao Li

University of Cambridge

Outline

1. Why is flux Pumping

2. What is flux pumping

3. How is flux pumping

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3. How is flux pumping

Why is flux pump

superconducting maglev train

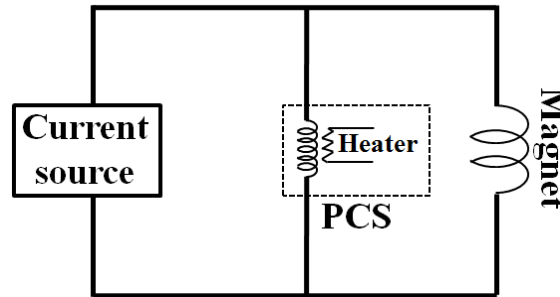
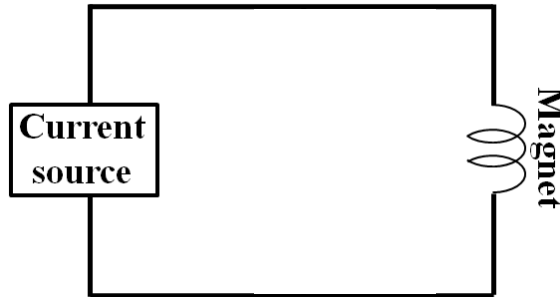
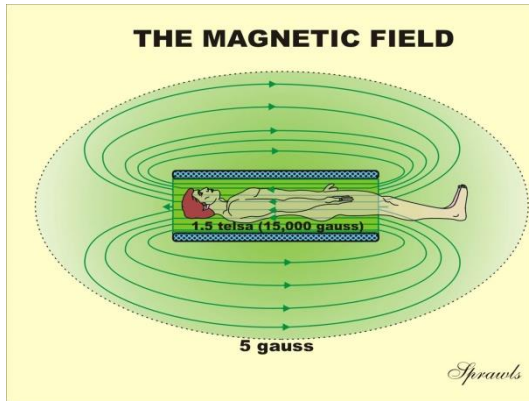
Large Hadron Collider

superconducting coil gun

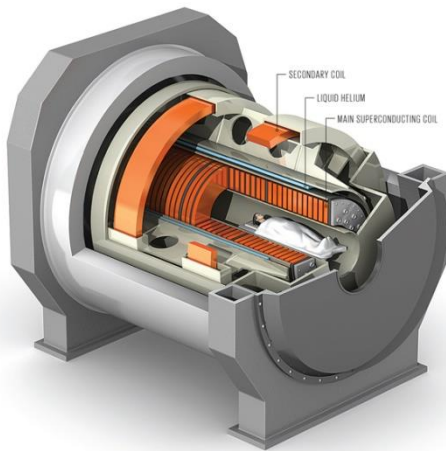


Why is flux pump

MRI: 1-10T the uniformity of magnetic field: 0.1ppm/h



400 Amp Cu Vs YBCO

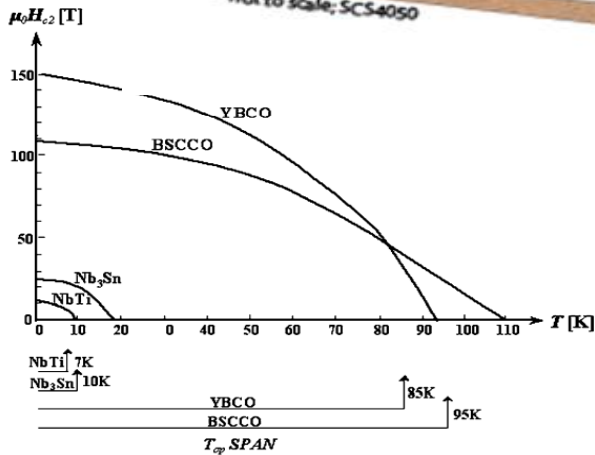
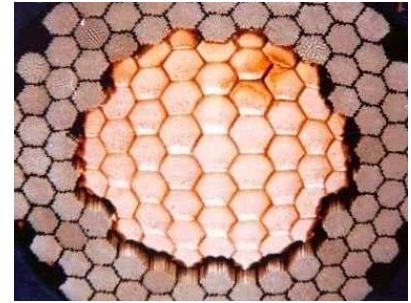
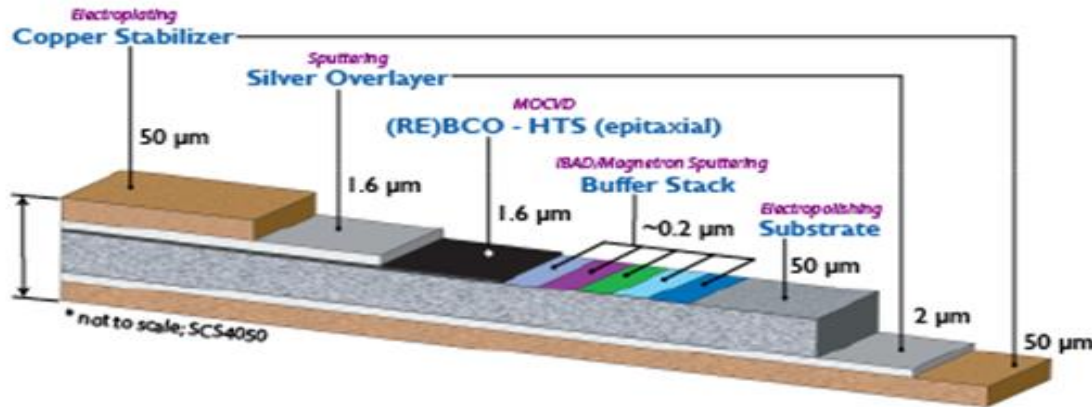


Limitation of HTS: 1. low-resistance joints 2. flux creep

Why is flux pump

LTS: wire, low-resistance joint

HTS: coated conductor, high resistance joint



NMR: above 20T, LTS plus HTS or copper

World record: 45.5T national laboratory in USA

Outline

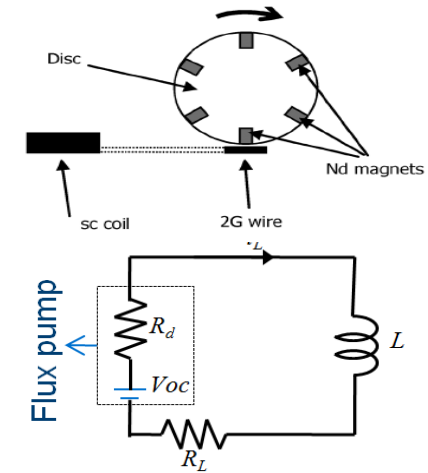
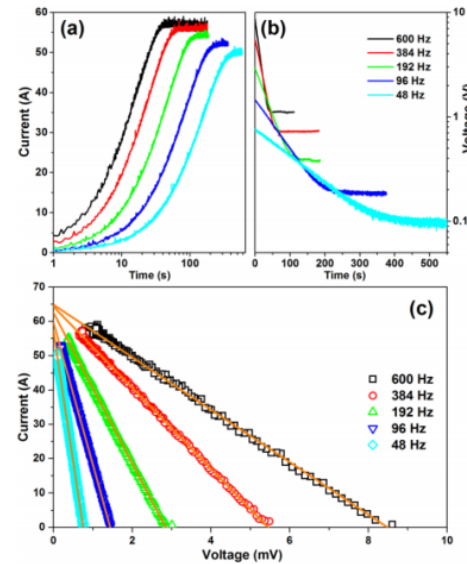
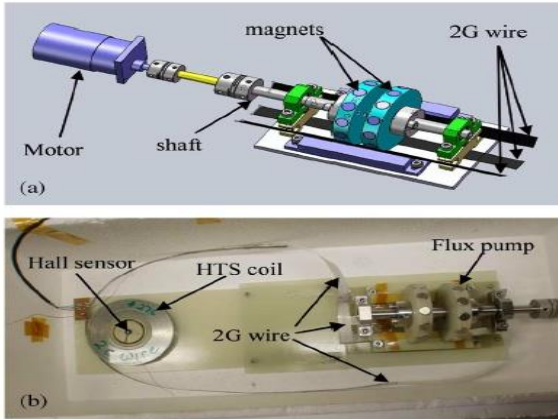
1. Why is flux Pumping

2. What is flux pumping

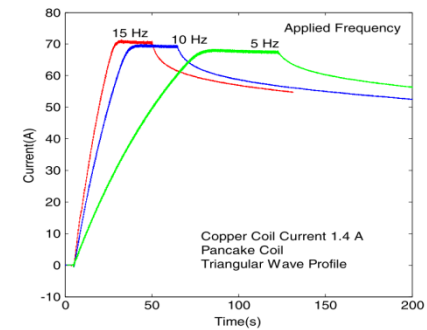
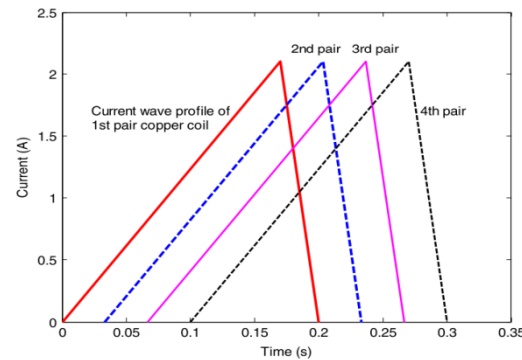
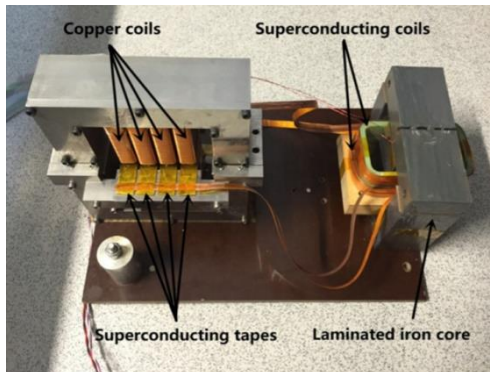
3. How is flux pumping

Travelling wave flux pump

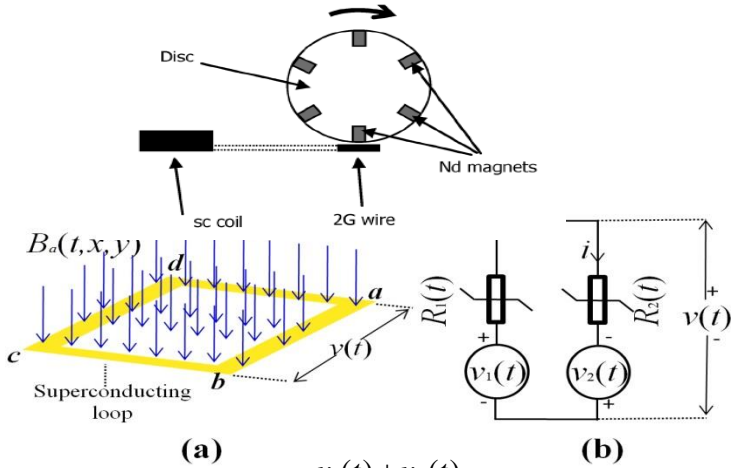
Rotating magnets type



Linear type:



Transformer-rectifier flux pump



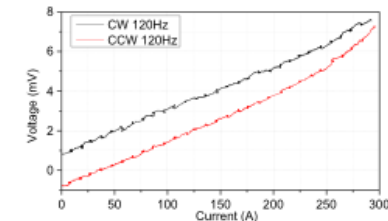
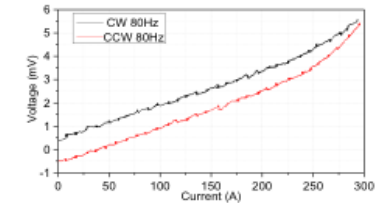
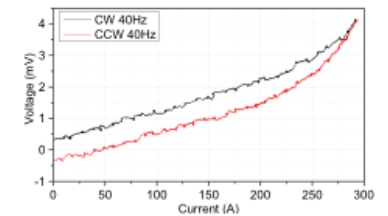
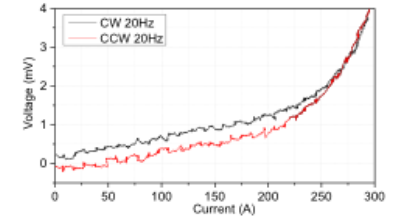
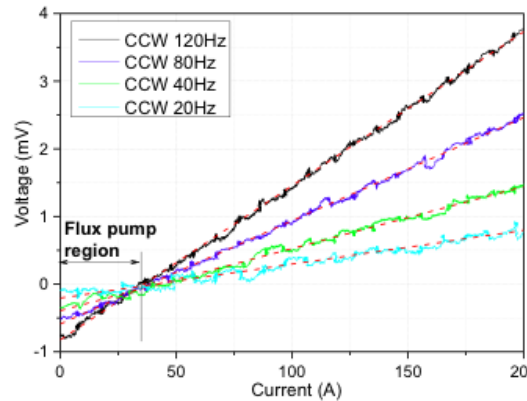
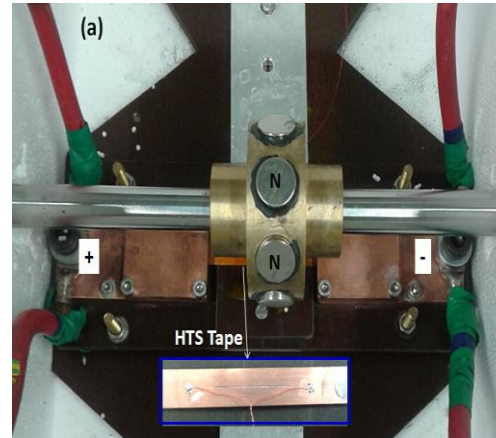
$$v(t) = iR_2(t) - v_2(t) = \frac{v_1(t) + v_2(t)}{R_1(t) + R_2(t)} R_2(t) - v_2(t)$$

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

Resistance constant

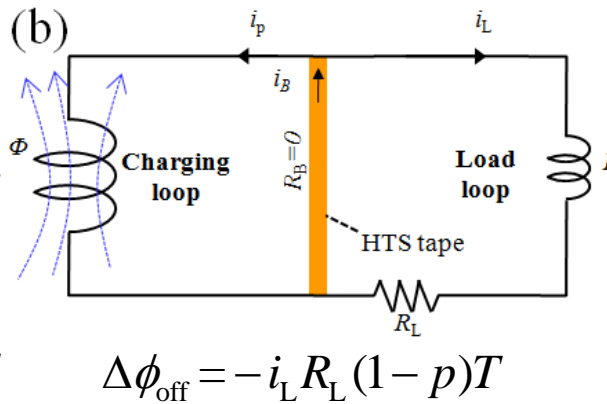
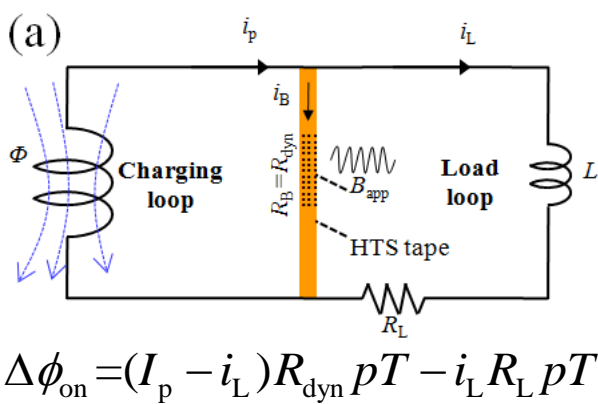
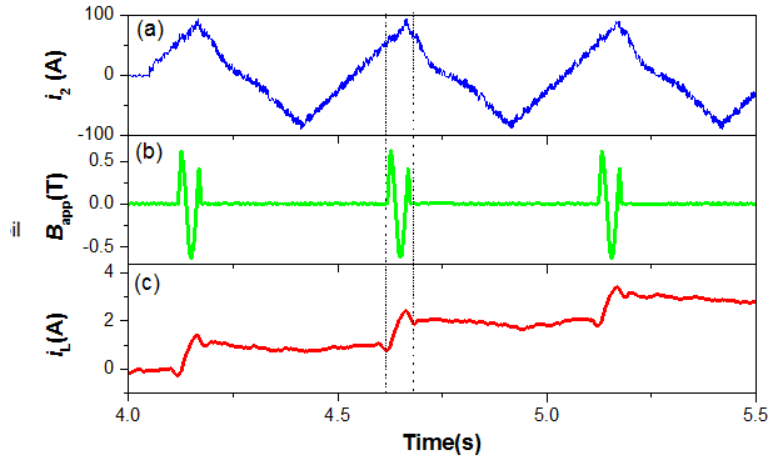
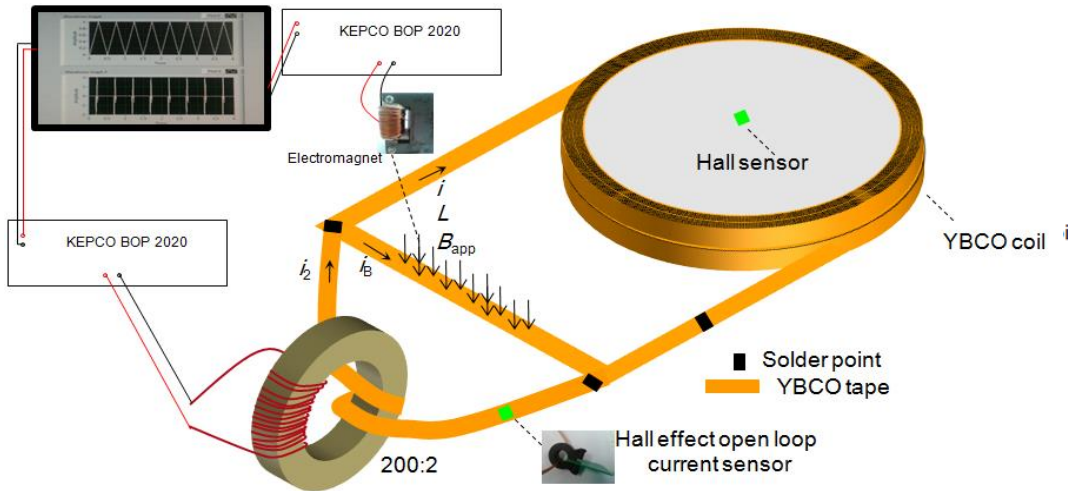
Resistance inconstant

$$V_{DC} = \frac{1}{T} \frac{R_2(t)}{R_1(t) + R_2(t)} \int_0^T -d\Phi / dt dt = 0 \quad V_{DC} = (p_{dec} - p_{inc}) \Delta\Phi \neq 0$$



J Geng, C Li, "Voltage-ampere of YBCO under inhomogeneous oscillating field", Applied Physics Letters 108 (26), 2016

Transformer-rectifier flux pump



$$\frac{\Delta\phi}{T} = L \frac{i_L}{dt} = I_p R_{dyn} p - i_L (R_{dyn} p + R_L)$$

$$\begin{cases} i_L = A(1 - e^{-t/\tau}) \\ A = I_p / (1 + R_L / R_{dyn} p) \\ \tau = L / (R_L + R_{dyn} p) \end{cases}$$

Outline

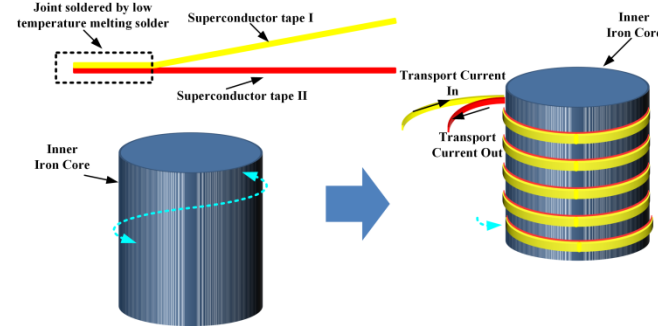
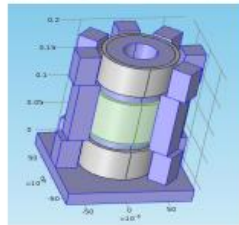
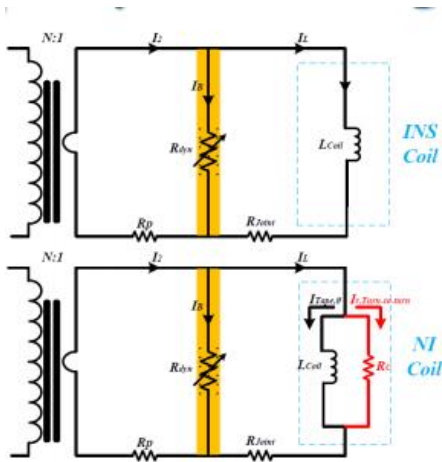
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Key technology in flux pumping

1、Novel design for persistent current switch (PCS)

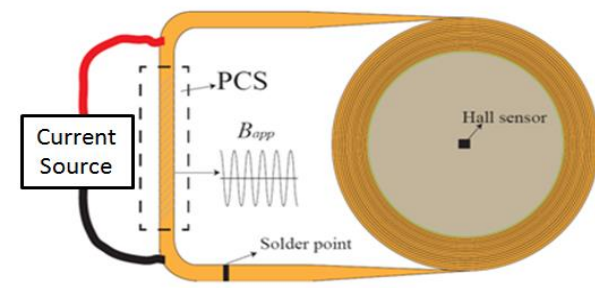
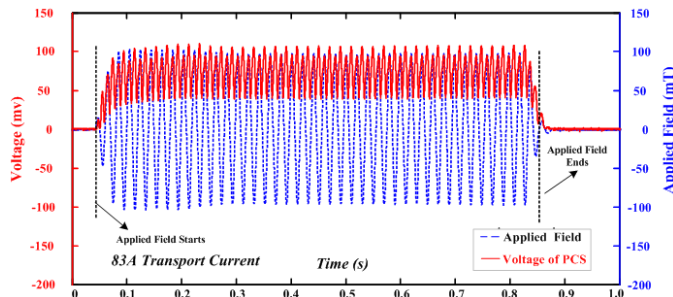


无感应电压

快速响应

恢复时间短

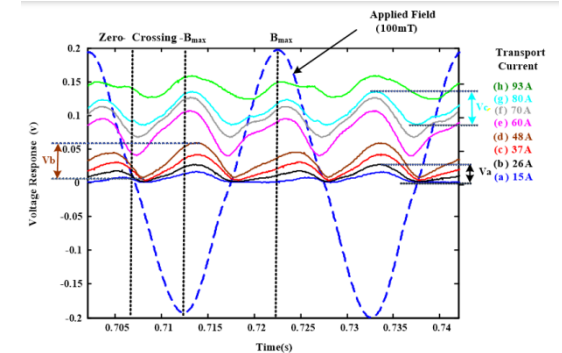
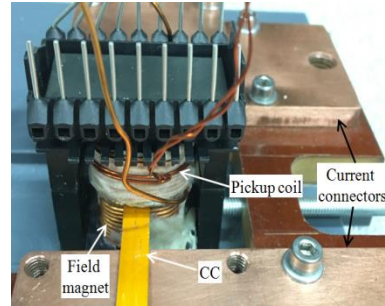
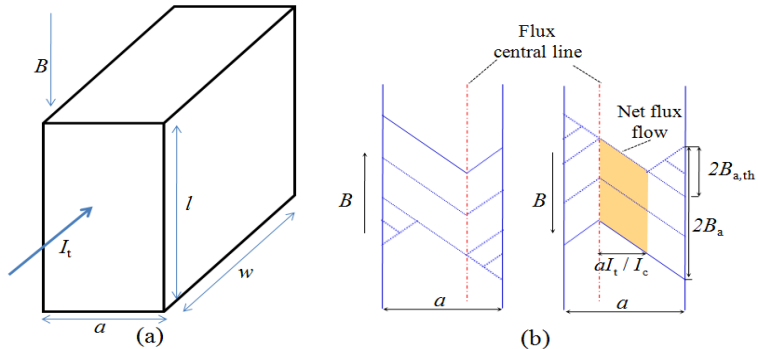
阻抗值可控



C Li, "Design for a persistent current switch controlled by ac magnetic field", *IEEE Trans. Appl. Supercond.* 28 (4), 2018
 C Li, "Persistent current switch for HTS superconducting magnets", *IEEE Trans. Appl. Supercond.* 29(2), 2019

Key technology in flux pumping

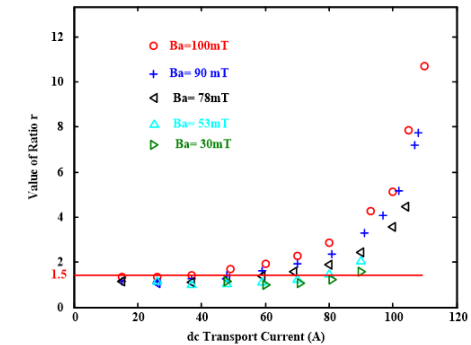
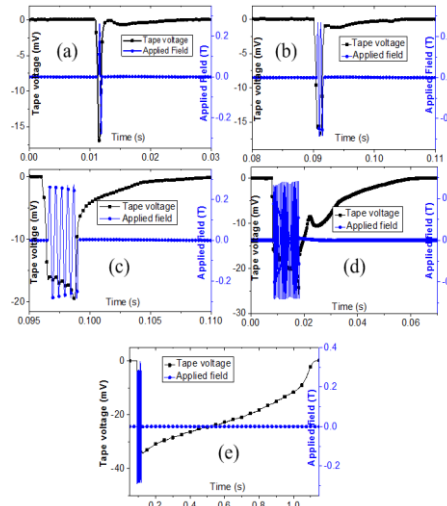
2. Second harmonic analysis to avoid the quench of PCS



$$\Phi_{\text{per_cycle}} = 2(B_a - B_{a,\text{th}})aI_t w / I_c$$

$$V_{\text{DC}} = f \Phi_{\text{per_cycle}} = 2f(B_a - B_{a,\text{th}})aI_t w / I_c$$

$$R_{\text{dyn}} = V_{\text{DC}} / I_t = 2awf(B_a - B_{a,\text{th}}) / I_c$$

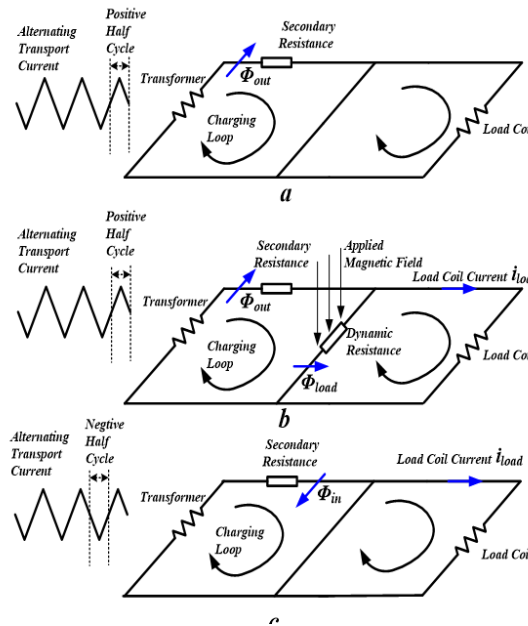
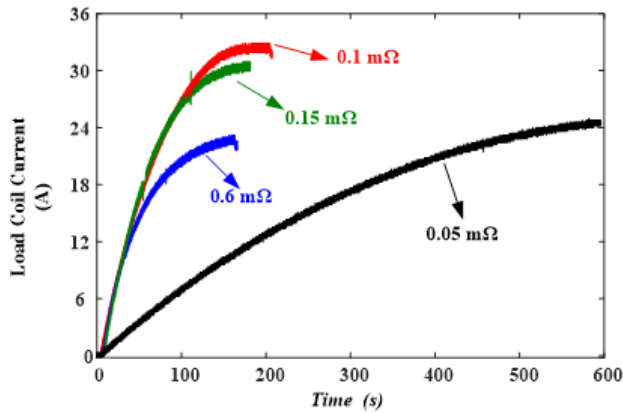
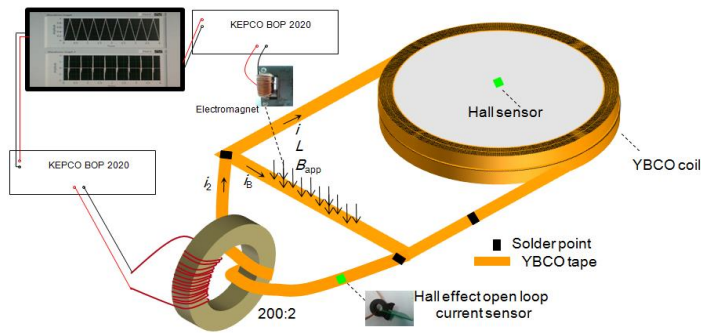


$$r = \frac{V_{\text{dc}}}{V_{2\text{nd-Harmonic}}}$$

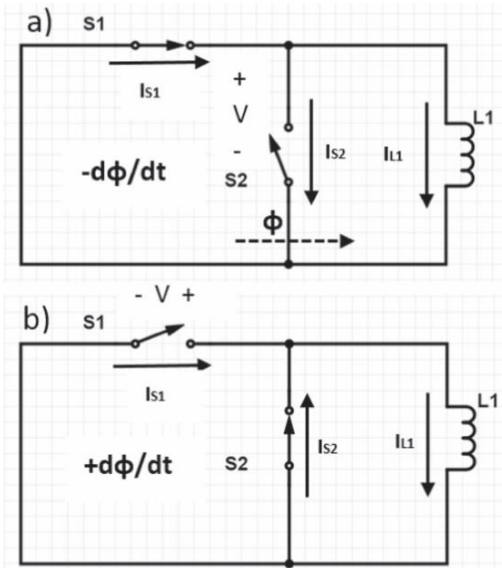
J Geng, C Li, "AC field controlled impedance: Response speed and electric field value", *IEEE Trans. Appl. Supercond.* 27 (6), 2017
 C LI, Tim, "Second harmonic in the voltage of dc-carrying YBCO tape under alternating magnetic field", *Physica C* 2019

Key technology in flux pumping

3. The secondary resistance



$$\phi_{out} < \phi_{in} \leq \phi_{out} + \phi_{load}$$



C Li, "Investigation on the Transformer-Rectifier Flux Pump for High Field Magnets", *IEEE Trans. Appl. Supercond.* 29 (4), 2019

Thank you