A Finite Element Calculation of Flux Pumping

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TOPICS

A low Tc Flux Pump

A high Tc Strip

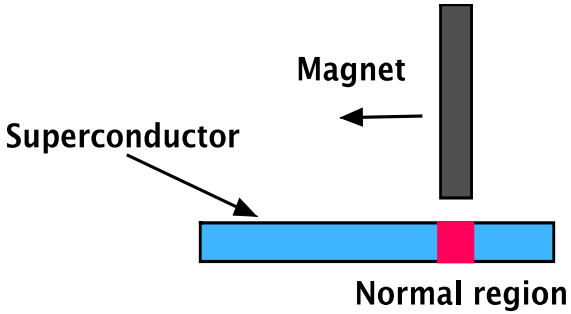
A thin Conductor

Two Thin Conductors

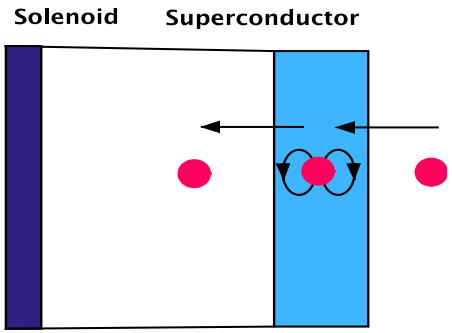
A circuit Model

Voltages

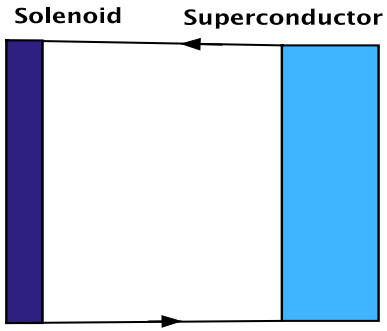
A Low T_c Flux Pump



Side View

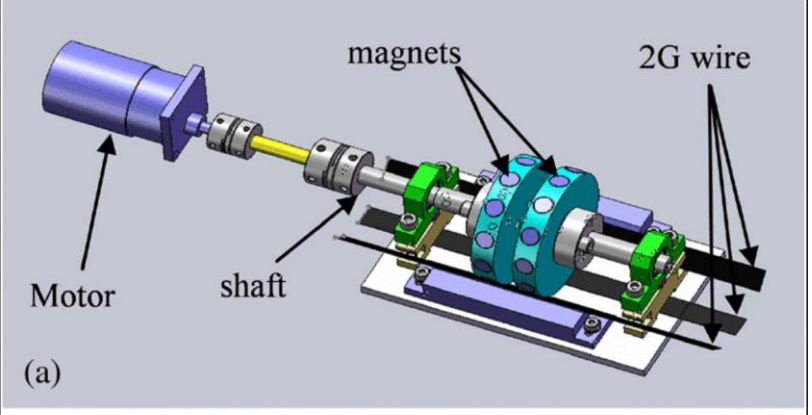


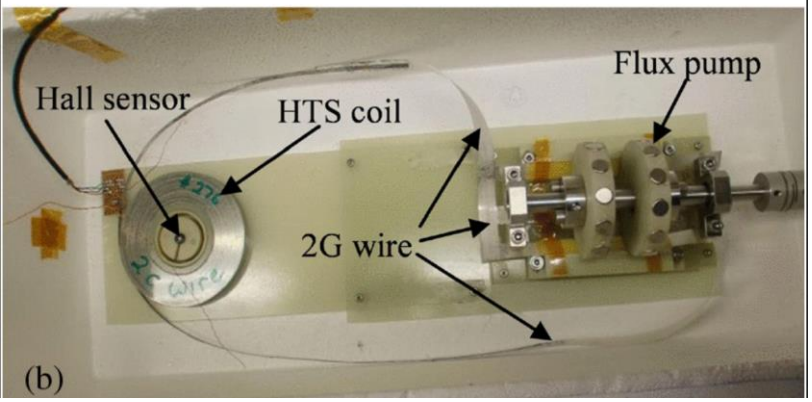
Plan View, induced current is shorted out locally. The magnet must be smaller than width of the superconductor



The magnet is removed. Currents are induced to keep flux the same.

The process is repeated.





A high Tc flux pump

We cannot drive the material normal.
What is the mechanism?

There is no direct interaction between a permanent magnets and individual flux lines.

It must be explicable in terms of the resistivity.

The magnet is the same width as the Tape

Published in: IEEE Transactions on Applied Superconductivity (Volume: 21, Issue: 3, June 2011)
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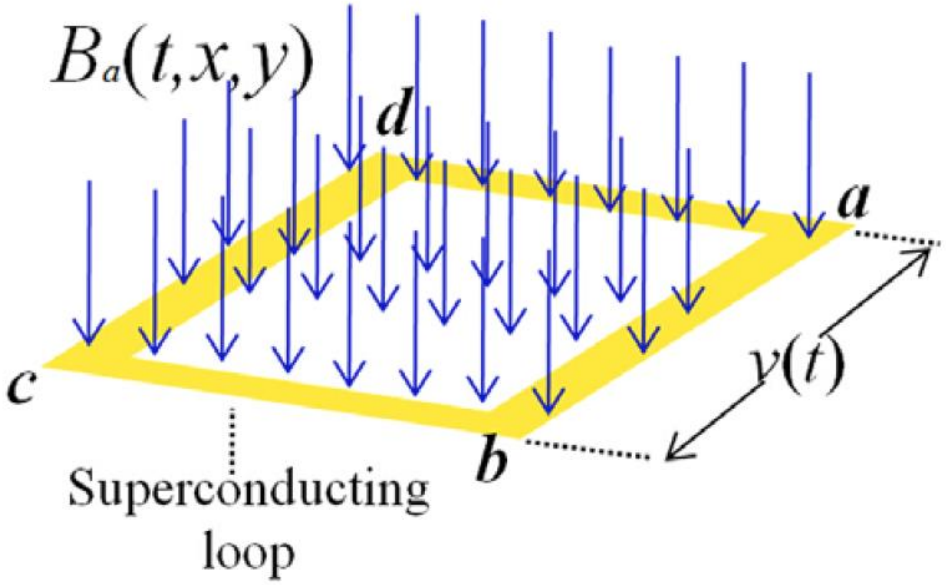
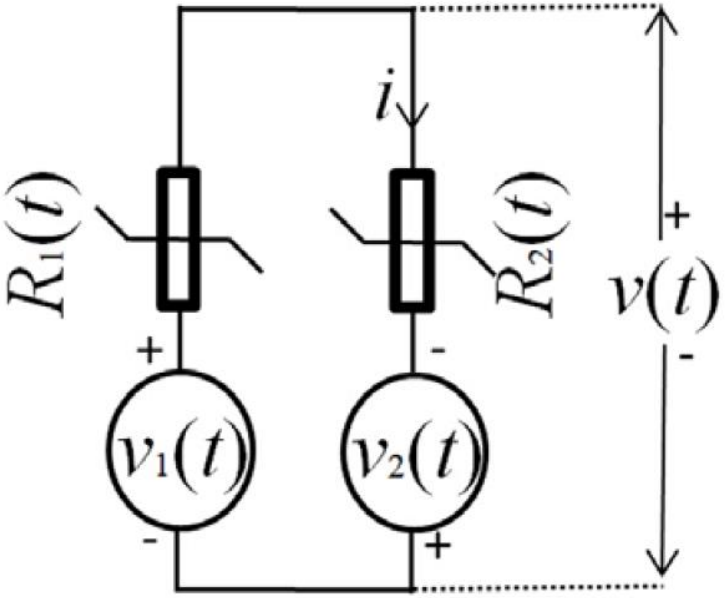




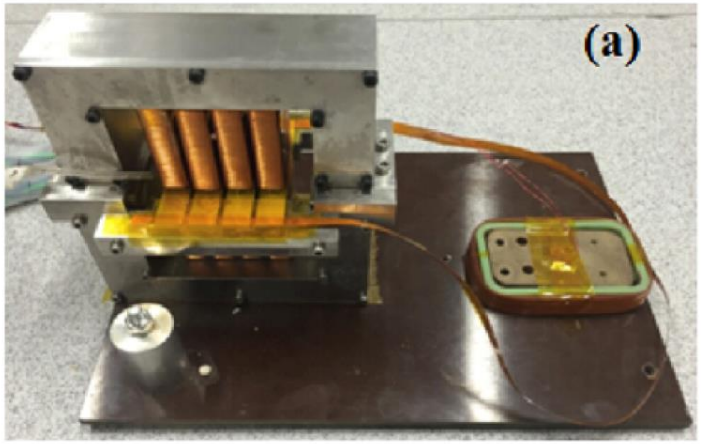
Origin of dc voltage in type II superconducting flux pumps: field, field rate of change, and current density dependence of resistivity

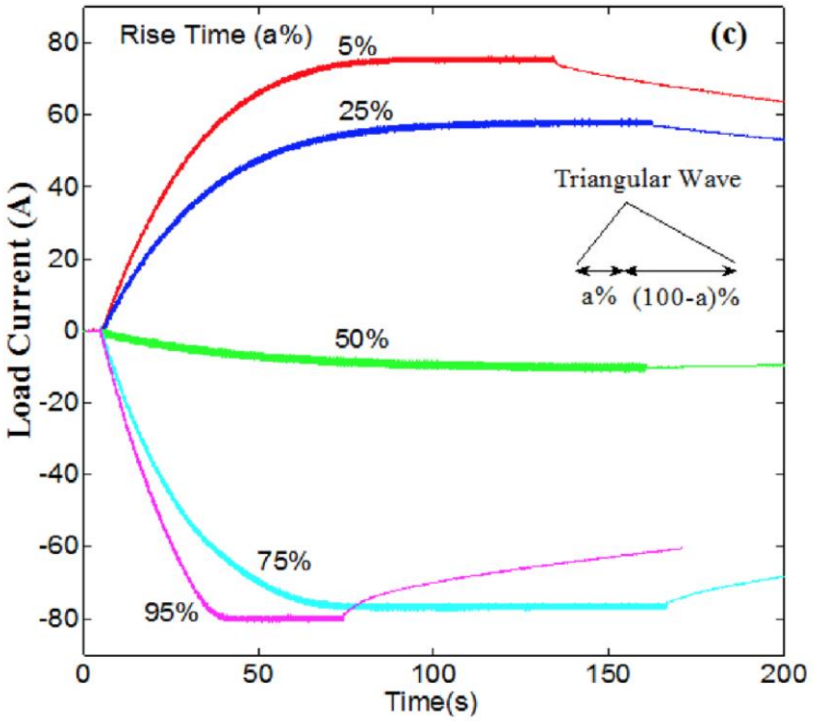
J Geng1, K Matsuda1,2, L Fu1, J-F Fagnard3, H Zhang1, X Zhang1, B Shen1,
Q Dong1, M Baghdadi1 and T A Coombs1

J. Phys. D: Appl. Phys. 49 (2016) 11LT01

Two strips takes the place of a single wide strip.

If the flux has different has different rates on increasing and decreasing the difference in the voltages leads to a DC voltage.





Flux pumped with a stationary magnet array. The induced current can be in either direction.

Proposed models use resistors and voltage sources.

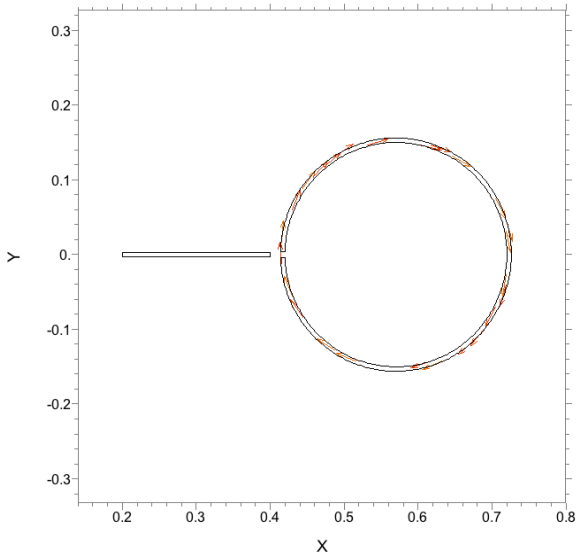
However we need to know how these parameters can be derived from the parameters of the pump.

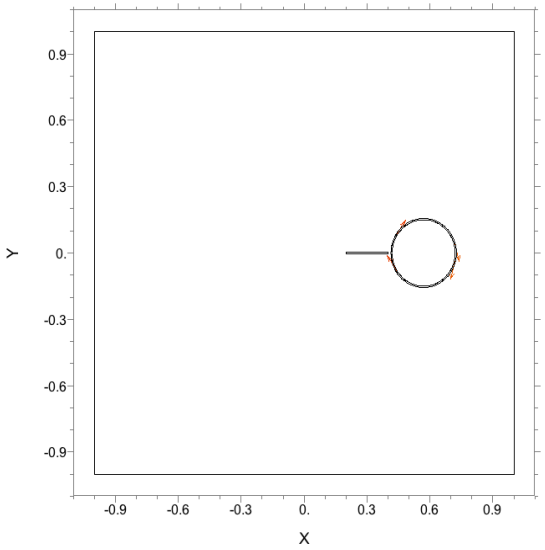
Therefore it it is useful to analyse a simple model which can be solved exactly.

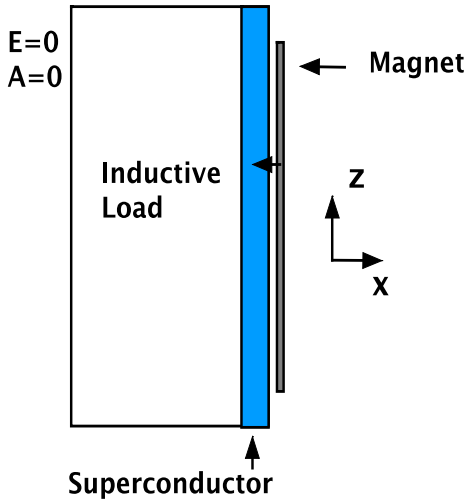
This model is based on the A formulation and the critical state Using FLEXpde.

Therefore the flux per cycle is independent of frequency.

A soluble 2D model







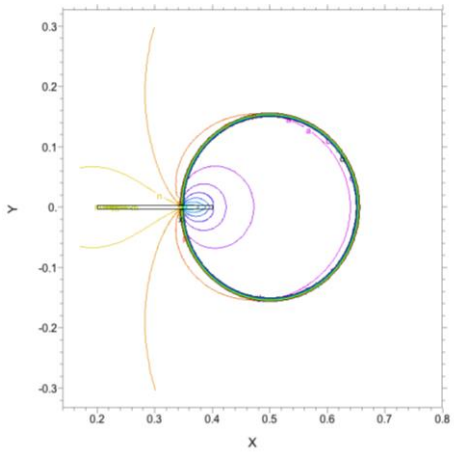
A magnet moves across a strip

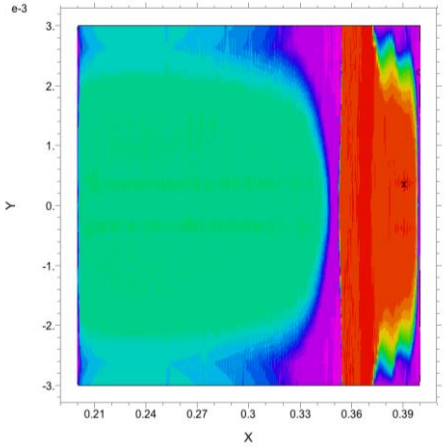
.

It is in In a superconducting box. The inductive load is the area to the left.

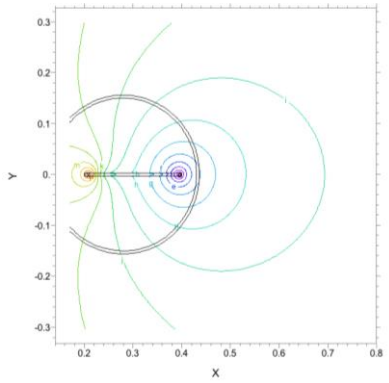
Side view

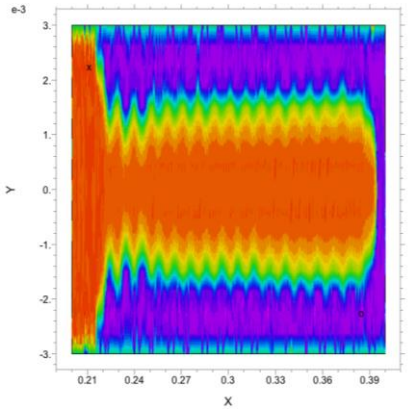
On completing the pass the magnet is turned off.





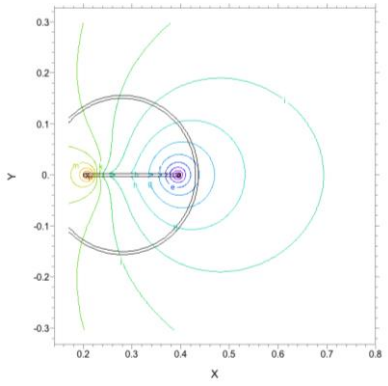
Start. Diamagnetic currents (red) on the edge.

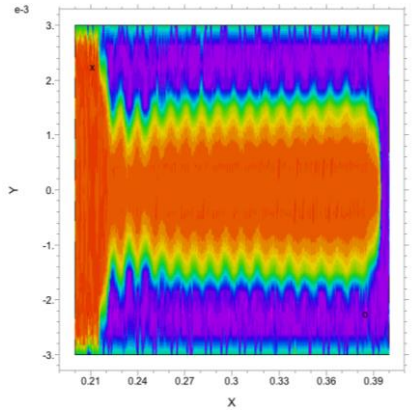




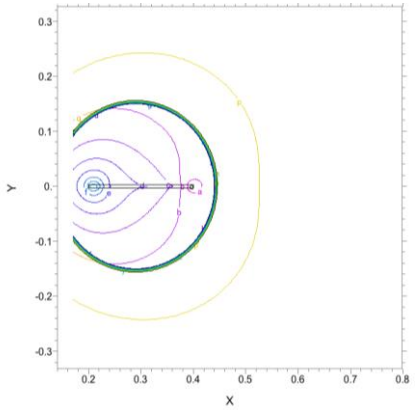
Complete pass. Diamagnetic currents at centre returned on the surface.

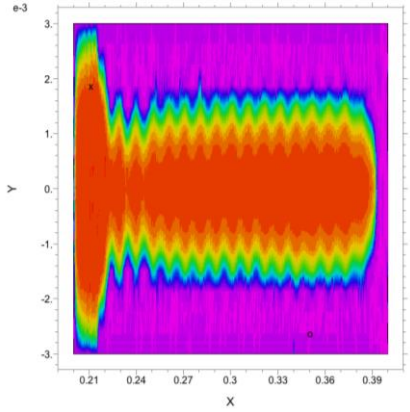
Note that the current induced by the moving magnet is in the opposite direction to the final pumped current.





Complete pass. Diamagnetic currents at centre returned on the surface

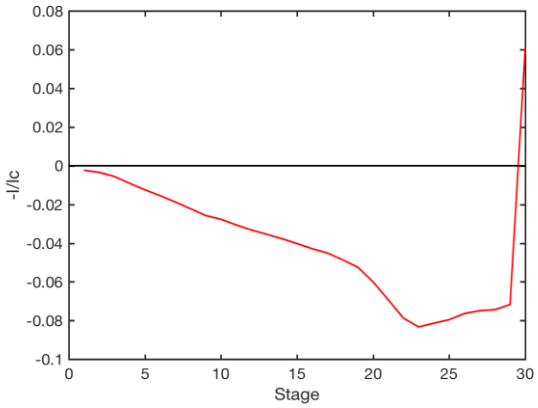




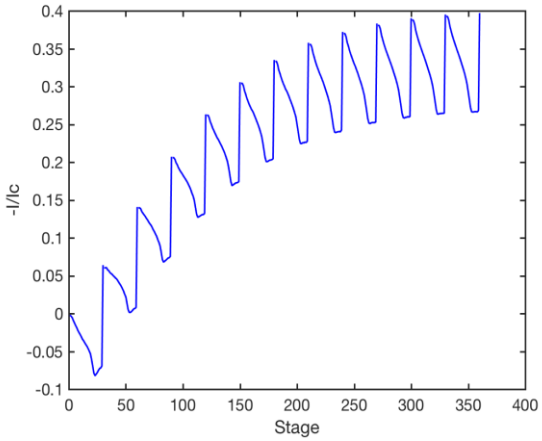
Magnet turned off. Induced EMF increases paramagnetic currents on surface. These give a net paramagnetic pumped current

The mean current density is about half Jc.

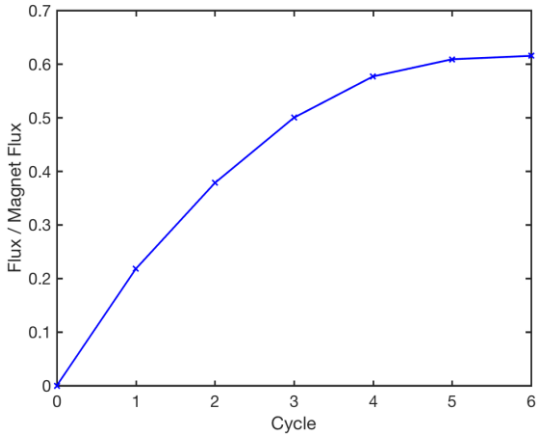
Wei Wang, and Tim Coombs.
Appl. Phys. Lett. 110 , 072601 (2017);



The current induced over one cycle.
Over most of the cycle the current is in the wrong direction. Only on turning off the magnet does a net pumped current appear.

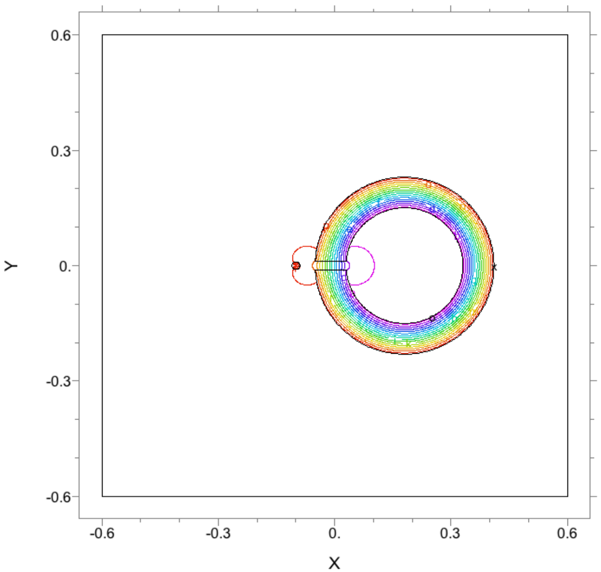


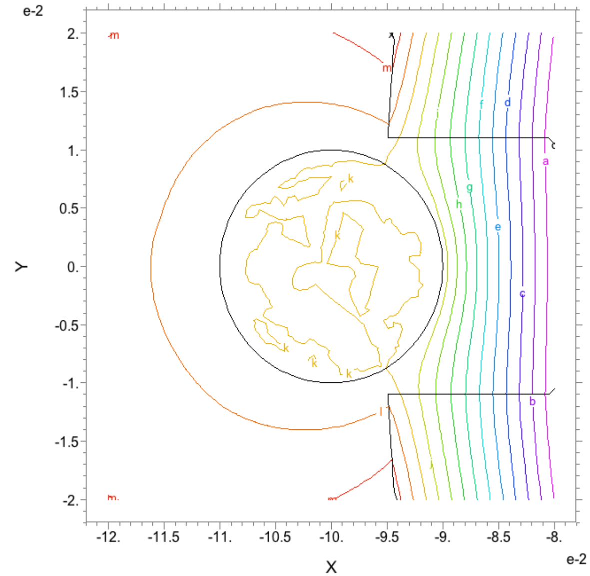
The currents up to saturation.

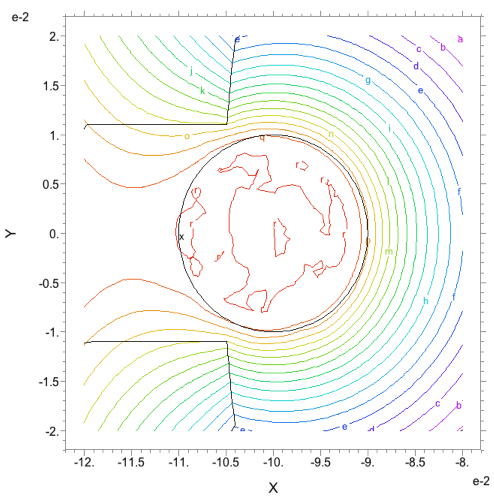


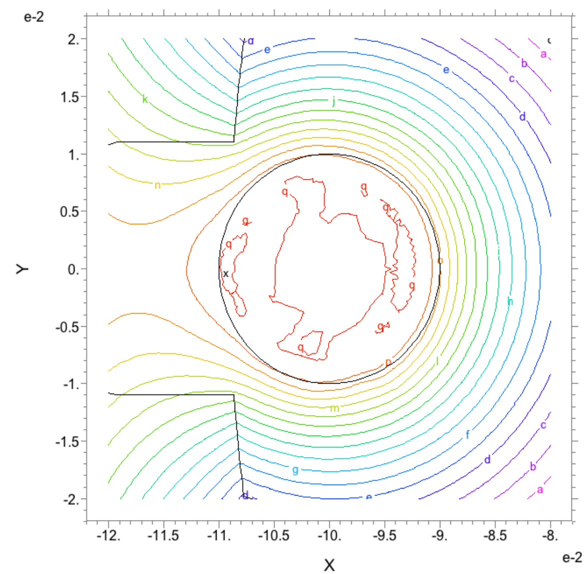
The net pumped current.
It saturates after six cycles.
The maximum flux pumped is 0.6 of the magnet flux.

Thin wire, I<Ic



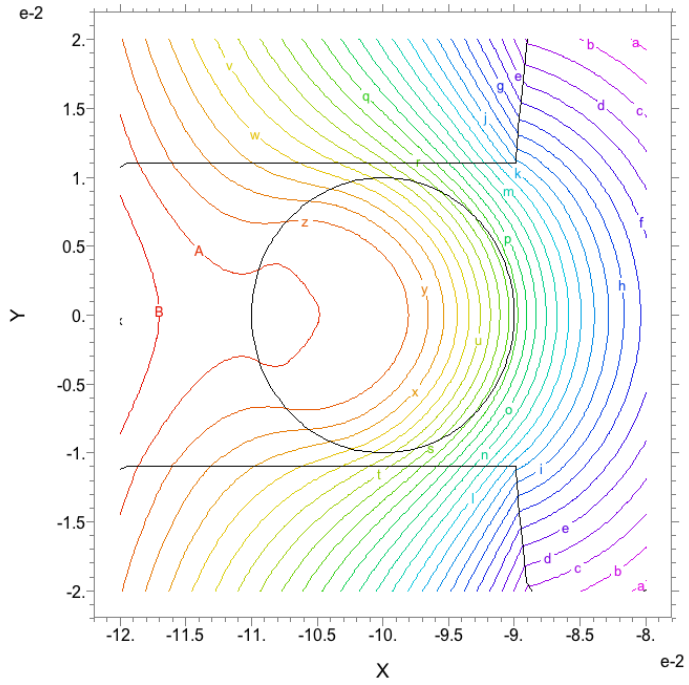


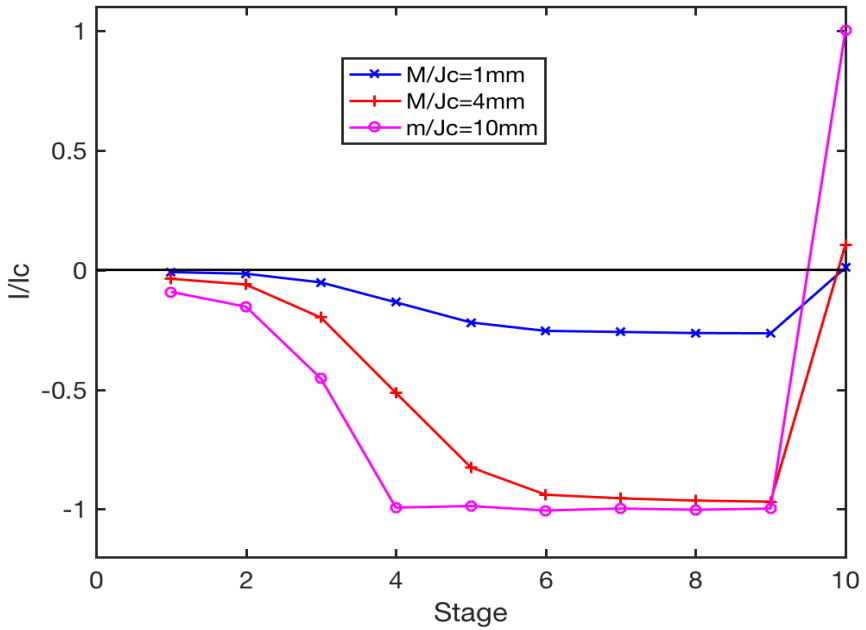




Effectively Type I reversible. No flux pumping.

I>Ic, Narrow Conductor

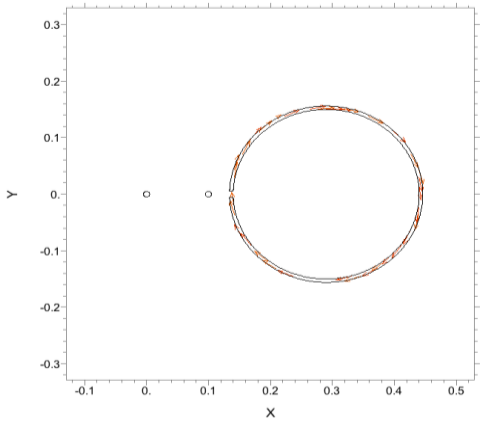


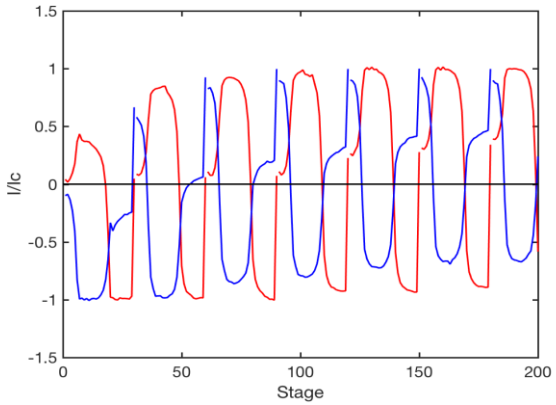


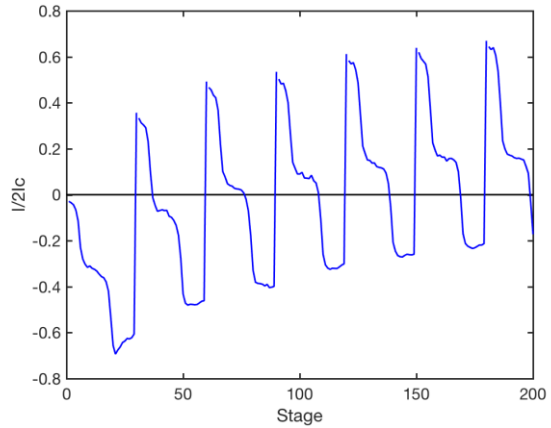
As soon as I>Ic the critical current is induced in the first cycle.
There is no significant flux pumping

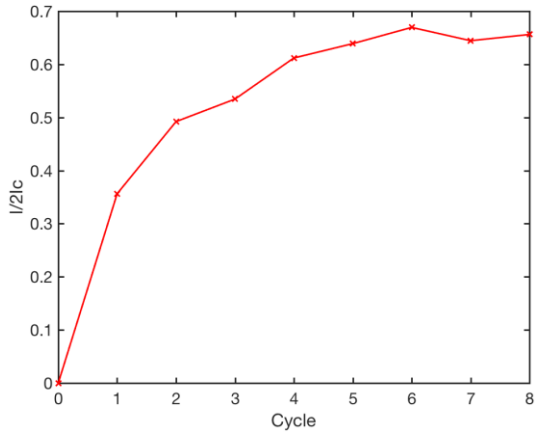
Two thin Wires.

The magnet must induce Ic in each wire at a different stage.
On crossing the first a diamagnetic current Ic is induced. Most of this flows in the second conductor but the difference goes into the load, in the wrong direction.
Again the maximum flux is less than the flux in the magnet.

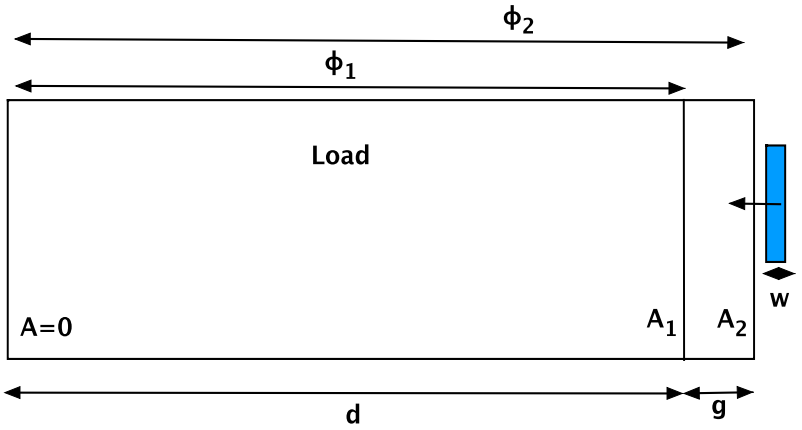








A Circuit Model in Terms of inductances

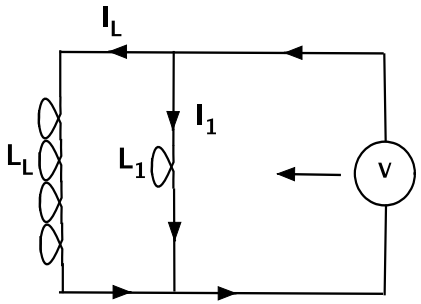


Flux inside inner conductor

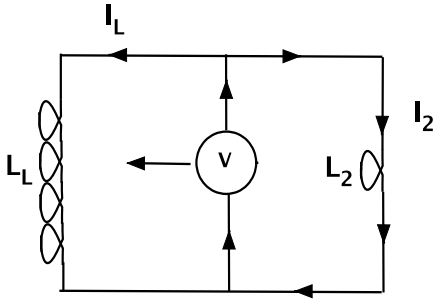
$$A_2 = (\mu_o / 2\pi)\{I_1 \ln(2d/g+1) + I_2 \ln(2[d+g]/r) + f_2\}$$

Flux inside outer conductor

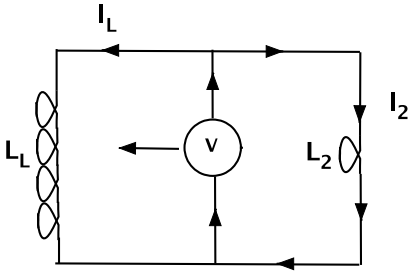
$$A_1 = (\mu_o / 2\pi)\{I_1 \ln(2d/r) + I_2 \ln(2d/g+1) + \phi_1\}$$



First cross. Current divides between inner conductor and load in inverse proportion to inductances. I1 large, IL small

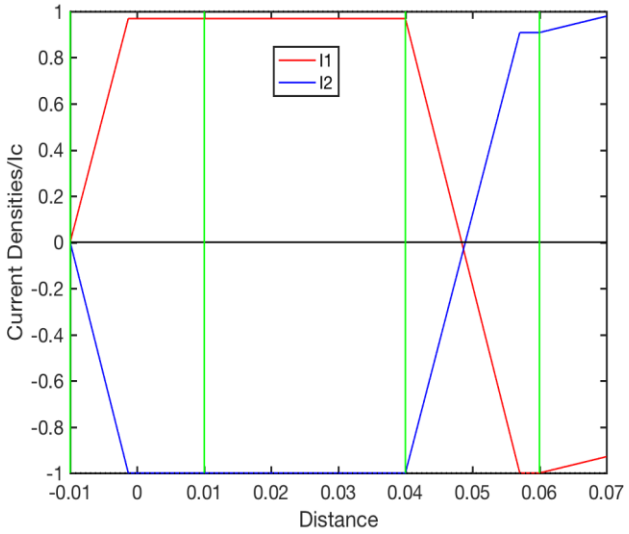


Second Cross. Currents divide between I1 and load in same proportion. Small increase in load Current

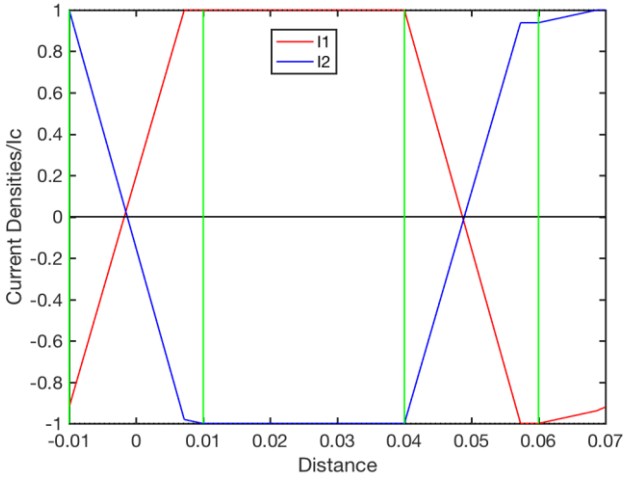


Magnet Turned off. Small reverse, pumped, current divides equally between outer and inner conductors giving ne paramagnetic current

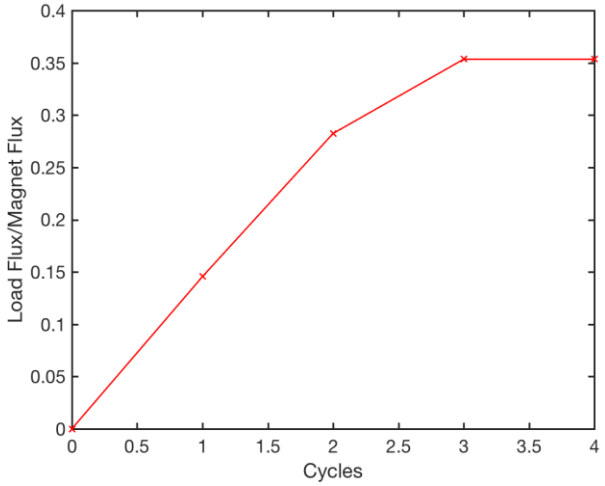
Inner distance 10^{20} times gap between conductors. Load inductance 17 times greater. Magnet field 10% above reversible value.

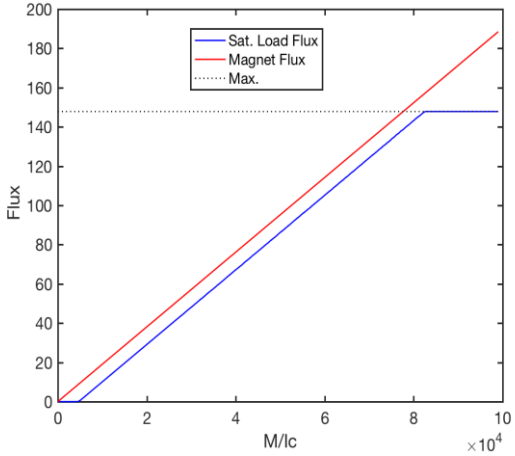


First Pass. Ic in outer.
Nearly -Ic in inner



After three cycles it saturates at 0.3 of magnet load

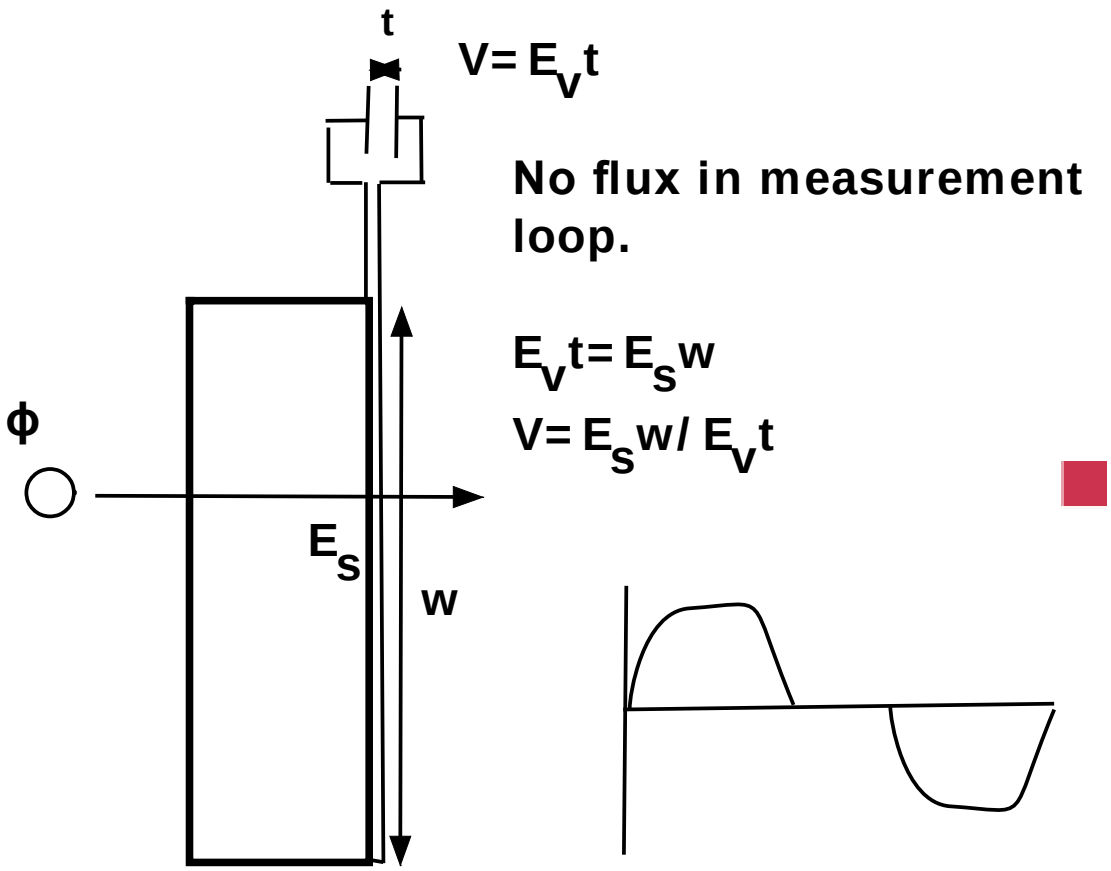


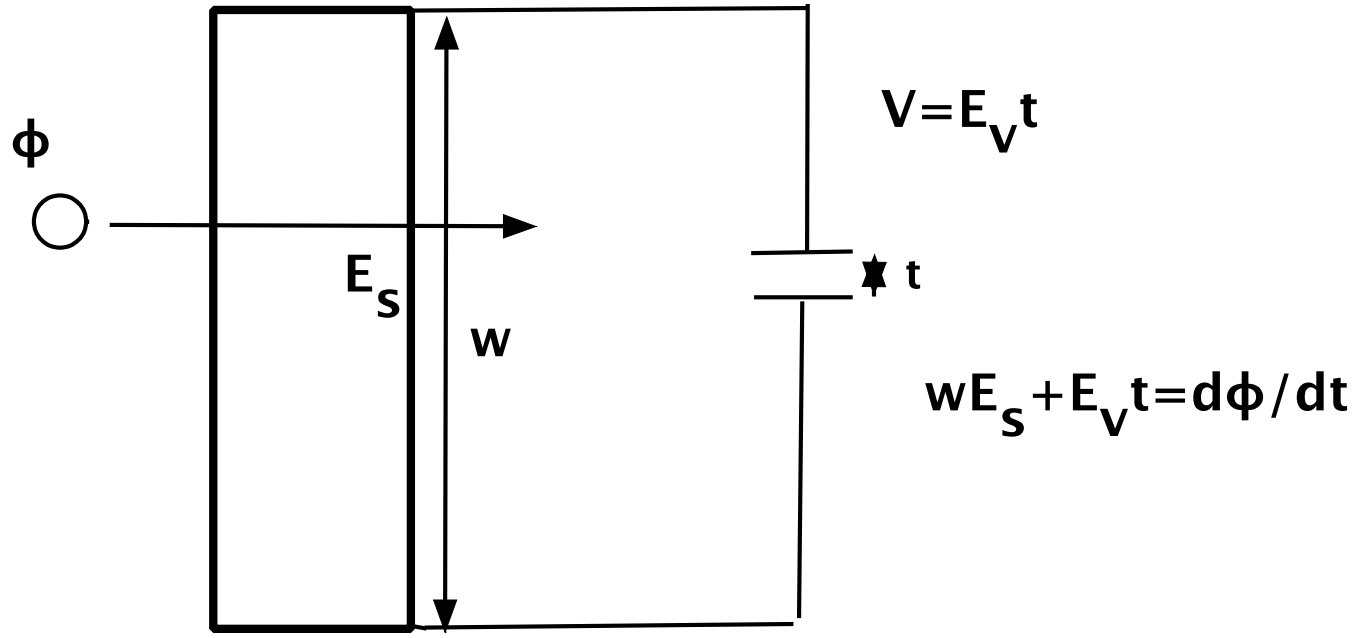


Higher magnet fields give immediate saturation.

Calculating circuit parameters in particular voltage requires care. A useful thought experiment is to use an electrostatic voltmeter and apply Faradays law.

$$\int E.dl = d\phi / dt$$





No voltage until magnet is turned off.

Conclusions

Flux pumping can be done using only the critical state model.

The results per cycle are independent of frequency and do not provide a useful flux pump into a large inductance. Nor do they reproduce the behaviour of practical flux pumps

We need to determine whether the deviation from the Bean model is due to the 'n' value, in which case the results are frequency dependent, or the variation of Jc with B, in which case they are not.

Interpretation of the 'voltage' from a flux pump requires care.