Force, torque and energy of machines with porous magnetisable wheels

M. Diebold, A. Kitanovski, D. Vuarnoz, P.W. Egolf

University of Applied Sciences of Western Switzerland

Introduction

Magneto-Caloric effect is a relation between magnetisation and temperature .

Possibles applications:

- Magnetic cooling
- Magnetic heat pump
- Magnetic power generation
- Medecine (hyperthermal electromagnetic therapy)
- …

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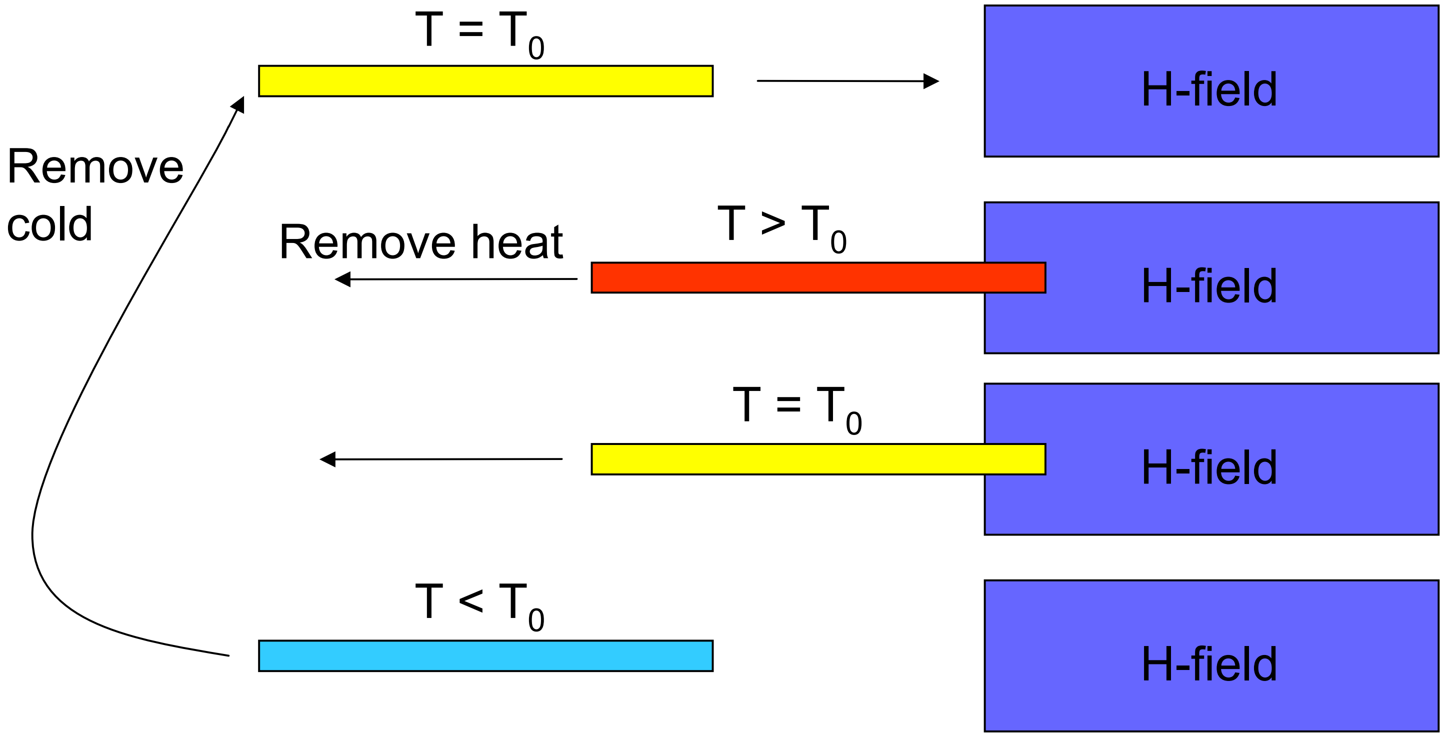
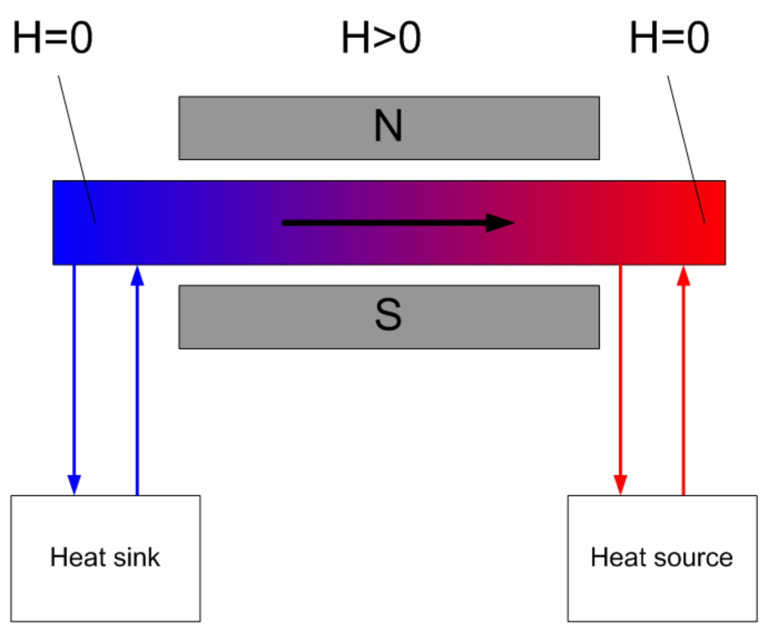
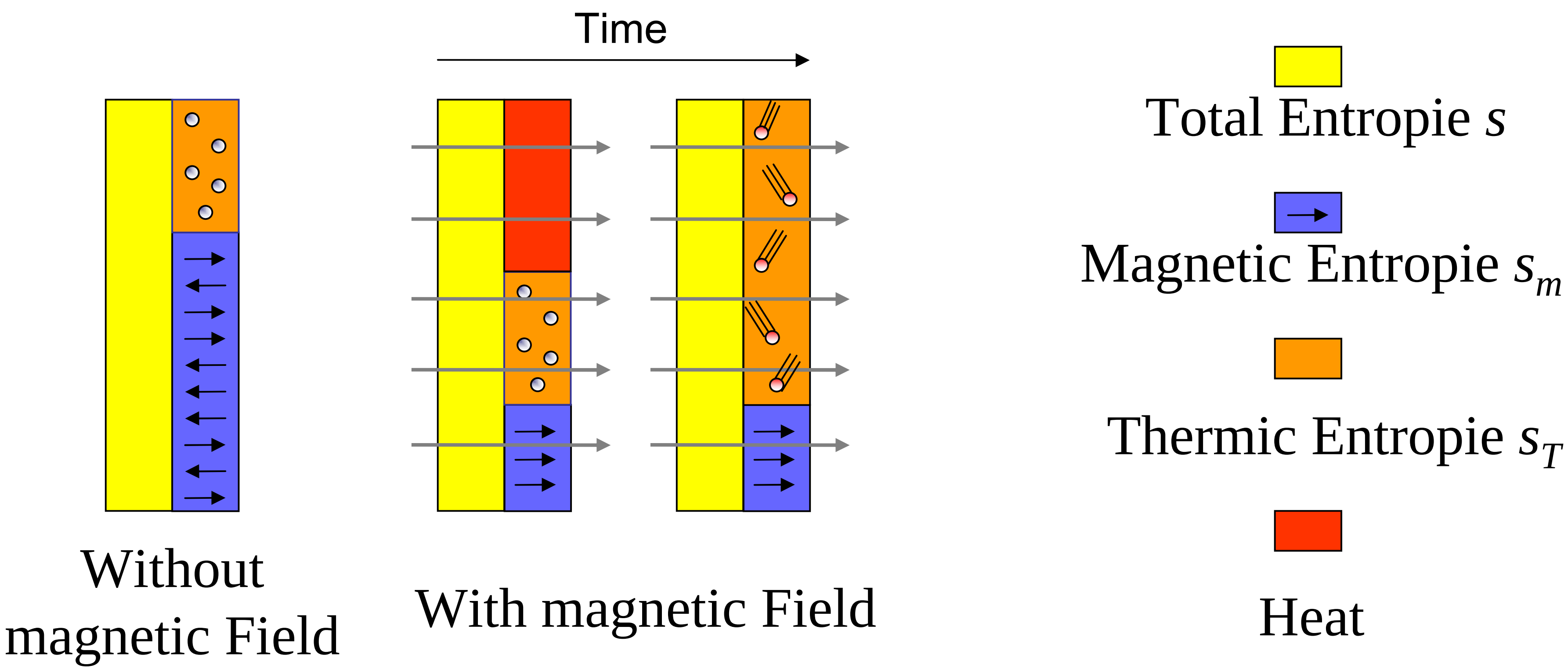
The MC effect for cooling or heating



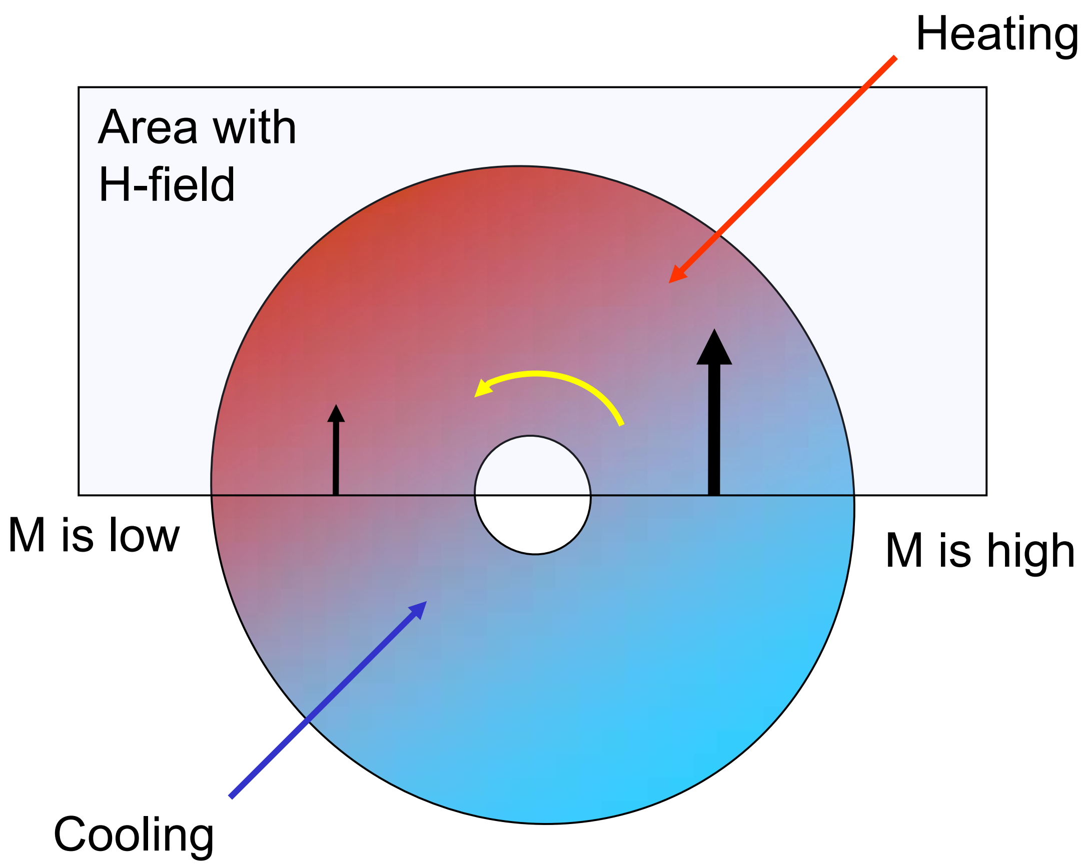
The MC effect for cooling or heating



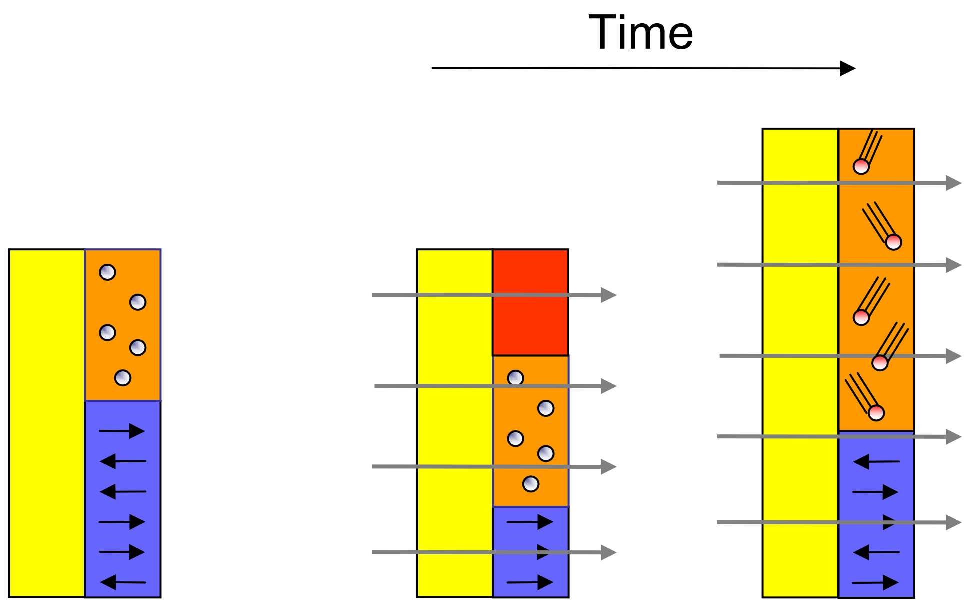
The MC effect for cooling or heating

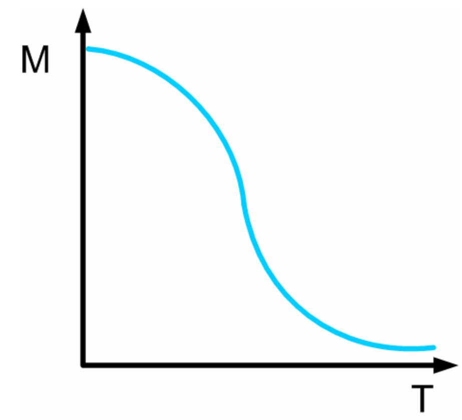


MC effect for power generation



MC effect for power generation





Total Entropie s

Magnetic Entropie s_m

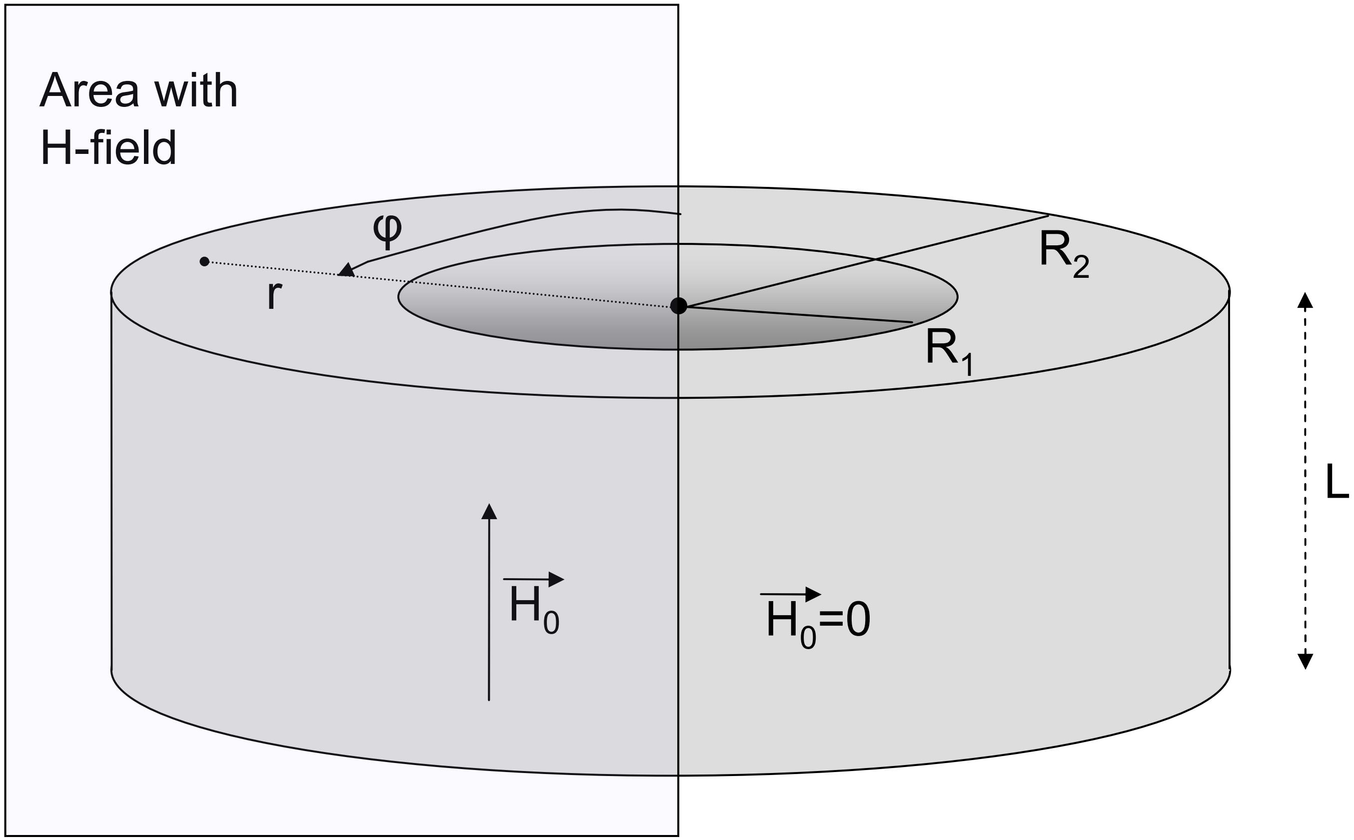
Thermic Entropie s_T

Heat

Without magnetic Field

With magnetic Field

Geometry



M. Diebold
A. Kitanovski
D. Vuarnoz
P.W. Egolf

Maxwell equations

$$dU = dQ + dW$$

Maxwell equations

$$rot\vec{E} + \frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0$$

$$div\vec{B} = 0$$

$$rot\vec{H} - \frac{1}{c}\frac{\partial \vec{D}}{\partial t} - j = 0$$

$$div\vec{D} - \rho = 0$$

$$c(\vec{H} rot\vec{E} - \vec{E} rot\vec{H}) + (\vec{H}\frac{\partial \vec{B}}{\partial t} + \vec{E}\frac{\partial \vec{D}}{\partial t}) + c\vec{E}\cdot\vec{j} = 0$$

$$dw = -\vec{H} d\vec{B}$$

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

$$\vec{B_0} = \mu_0 \vec{H_0}$$

$$dw = -\mu_0 \vec{H} d\vec{M} - \frac{\mu_0}{2} d(\vec{H}^2)$$

$$dw = -\mu_0 \vec{H} d\vec{M} - \mu_0 d\phi$$

$$\Rightarrow dW = -\mu_0 \int_\Omega \vec{H} d\vec{M} dV - \mu_0 d\Phi$$

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Work

$$dw = -\vec{H}\,d\vec{B}$$

$$\vec{B} = \mu_0(\vec{H} + \vec{M})$$

$$\vec{B_0} = \mu_0 \vec{H_0}$$

$$dw = -\mu_0 \vec{H}\,d\vec{M} - \frac{\mu_0}{2} d(\vec{H}^2)$$

$$dw = -\mu_0 \vec{H}\,d\vec{M} - \mu_0 d\phi$$

$$\Rightarrow dW = -\mu_0 \int_\Omega \vec{H}\,d\vec{M}\,dV - \mu_0 d\Phi$$

$$dW_1 = dW - dW_0 = -\int_\Omega \vec{H}\,d\vec{B}\,dV + \int_\Omega \vec{H_0}\,d\vec{B_0}\,dV$$

$$dw_1 = -\vec{B_0}\left(\frac{1}{\mu_0} d\vec{B} - d\vec{H}\right)$$

$$dw_1 = dw_1^{(ext)} = -\mu_0 \vec{H_0}\,d\vec{M}$$

Kelvin force

Analogy with vapour compression processes

$$\Delta w_1^{(abs)} = -\Delta(pv) = -(p^{(2)}v^{(2)} - p^{(1)}v^{(1)})$$

$$\left.\begin{aligned} dw_1^{(abs)} &= -d(pv) \\ dW_1^{(ext)} &= \vec{F}\cdot d\vec{s} = pAds = -pdV \\ dw_1^{(tech)} &= -(dw_1^{(abs)} - dw_1^{(ext)}) \end{aligned}\right\} \Rightarrow dw_1^{(tech)} = d(pv) - pdv = vdp$$

Application on magnetism

$$\left.\begin{aligned} dw_1^{(abs)} &= -\mu_0 d(\overrightarrow{H_0}\overrightarrow{M}) \\ dw_1^{(ext)} &= -\mu_0 \overrightarrow{H_0} d\overrightarrow{M} \\ dw_1^{(tech)} &= -(dw_1^{(abs)} - dw_1^{(ext)}) \end{aligned}\right\} \Rightarrow dw_1^{(tech)} = \mu_0 \overrightarrow{M} d\overrightarrow{H_0}$$

Kelvin force

$$\vec{F} = \mu_0 \int_\Omega \sum M_i \nabla H_{0i} dV_R$$

Kelvin force II

Force density

$$f = \mu_0 \sum M_i \nabla H_{0i} = \mu_0 \begin{bmatrix} M_\phi \frac{1}{r}\frac{\partial}{\partial \phi} H_{0\phi} + M_r \frac{1}{r}\frac{\partial}{\partial \phi} H_{0r} + M_z \frac{1}{r}\frac{\partial}{\partial \phi} H_{0z} \\ M_\phi \frac{\partial}{\partial r} H_{0\phi} + M_r \frac{\partial}{\partial r} H_{0r} + M_z \frac{\partial}{\partial r} H_{0z} \\ M_\phi \frac{\partial}{\partial z} H_{0\phi} + M_r \frac{\partial}{\partial z} H_{0r} + M_z \frac{\partial}{\partial z} H_{0z} \end{bmatrix}$$

Field parallel to z-axis $\Rightarrow \begin{cases} H_\phi \equiv 0 \\ H_r \equiv 0 \end{cases}$

Field changes only along Φ-axis $\Rightarrow \begin{cases} \frac{\partial}{\partial r} H_{0z} \equiv 0 \\ \frac{\partial}{\partial z} H_{0z} \equiv 0 \end{cases}$

M. Diebold
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Kelvin force III

Force density: $$f_{\phi} = \mu_0 M_z \frac{1}{r} \frac{\partial}{\partial \phi} H_{0z}$$

Integration and with packing factor ψ:

$$F_{\phi} = \psi \mu_0 \int_0^L \int_{R_1}^{R_2} \int_0^{2\pi} M_i \nabla H_{0i} \, d\phi \, r \, dr \, dz$$

$$= \psi \mu_0 L \int_{R_1}^{R_2} \int_0^{2\pi} M_z \frac{\partial}{\partial \phi} H_{0z} \, d\phi \, dr$$

Heaviside's and Dirac's distribution

Important areas: entrance (Φ=0) and exit (Φ=π)

Use of Heaviside distribution:

$$F_\phi = \psi\mu_0 L H_{0z}\left[\int_{R_1}^{R_2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} M_z \frac{\partial}{\partial\phi}\theta(\phi)\,d\phi\,dr + \int_{R_1}^{R_2}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} M_z \frac{\partial}{\partial\phi}\theta(\pi-\phi)\,d\phi\,dr\right]$$

Heaviside to Dirac distribution:

$$F_\phi = \psi\mu_0 L H_{0z}\left[\int_{R_1}^{R_2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} M_z\delta(\phi)\,d\phi\,dr + \int_{R_1}^{R_2}\int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} M_z\delta(\pi-\phi)\,d\phi\,dr\right]$$

Force density:

$$\tilde{f}_\phi = \psi\mu_0 L H_{0z}\left[M_z(r,0) - M_z(r,\pi)\right]$$

Torque and mechanical work

Torque

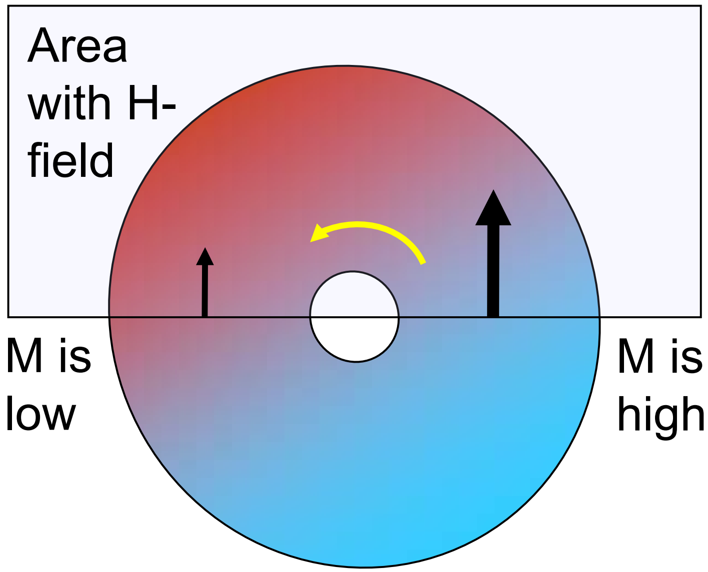
$$M = \int_{R_1}^{R_2} \widetilde{f_\phi} r dr = \psi \mu_0 L H_{0z} \int_{R_1}^{R_2} \left[M_z(r,0) - M_z(r,\pi) \right] r dr$$

Work over one turn

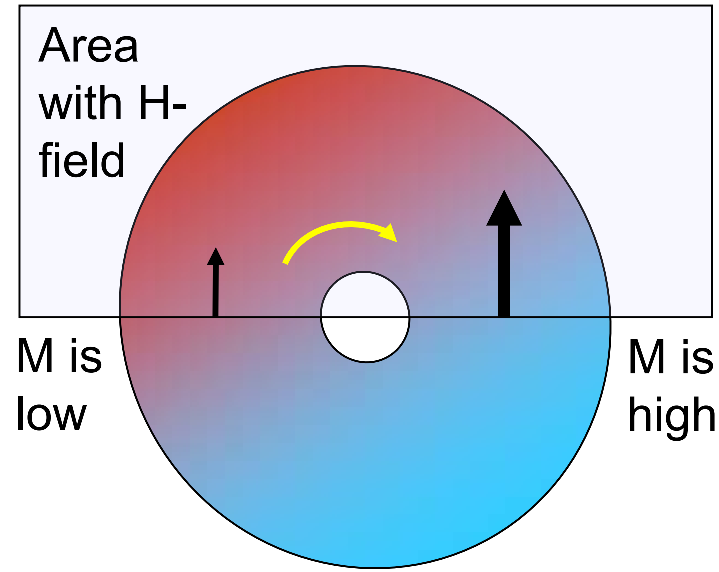
$$dW = M d\phi$$

$$\Rightarrow W = 2\pi \psi \mu_0 L H_{0z} \int_{R_1}^{R_2} \left[M_z(r,0) - M_z(r,\pi) \right] r dr$$

Power generator and cooling machine



Power generator:
Movement due to torque



Cooling machine:
Torque is opposed to the movement

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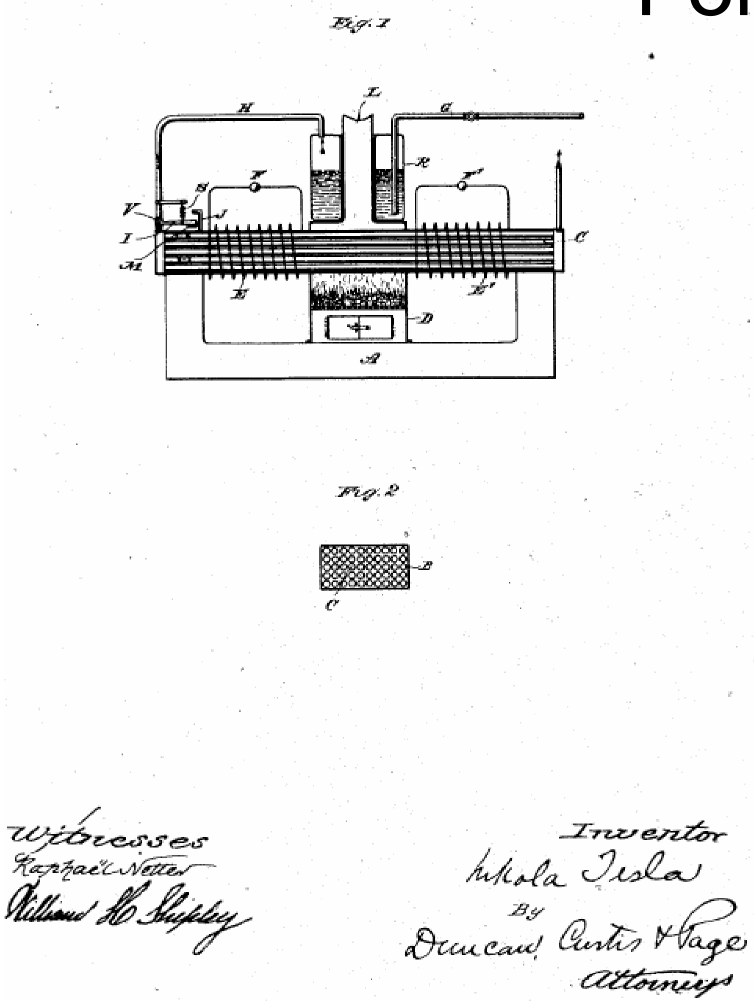
Former ideas



N. Tesla, Pyromagneto-electric generator, US patent 428,057, May 18, 1890.

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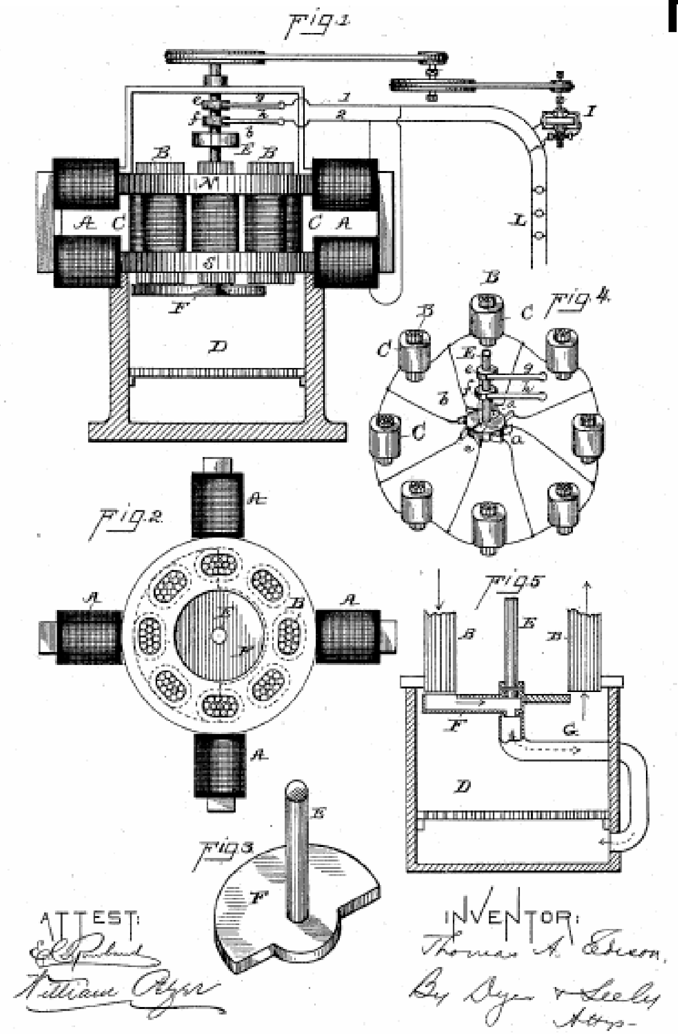
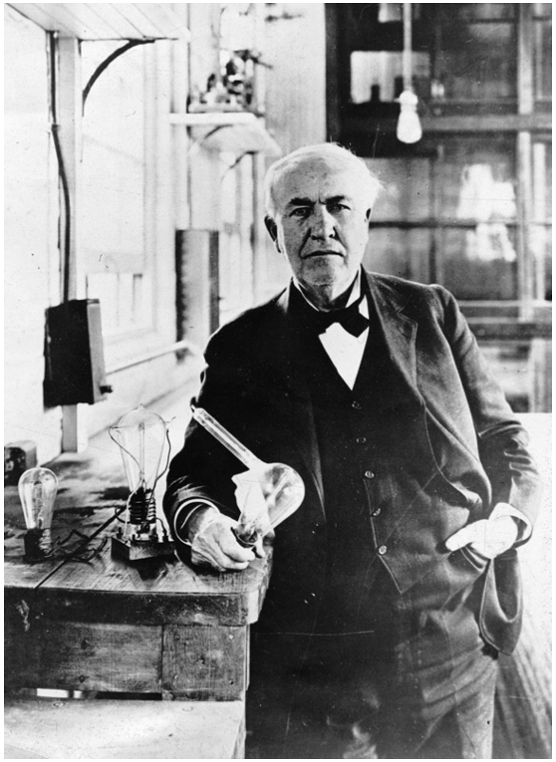
Former ideas



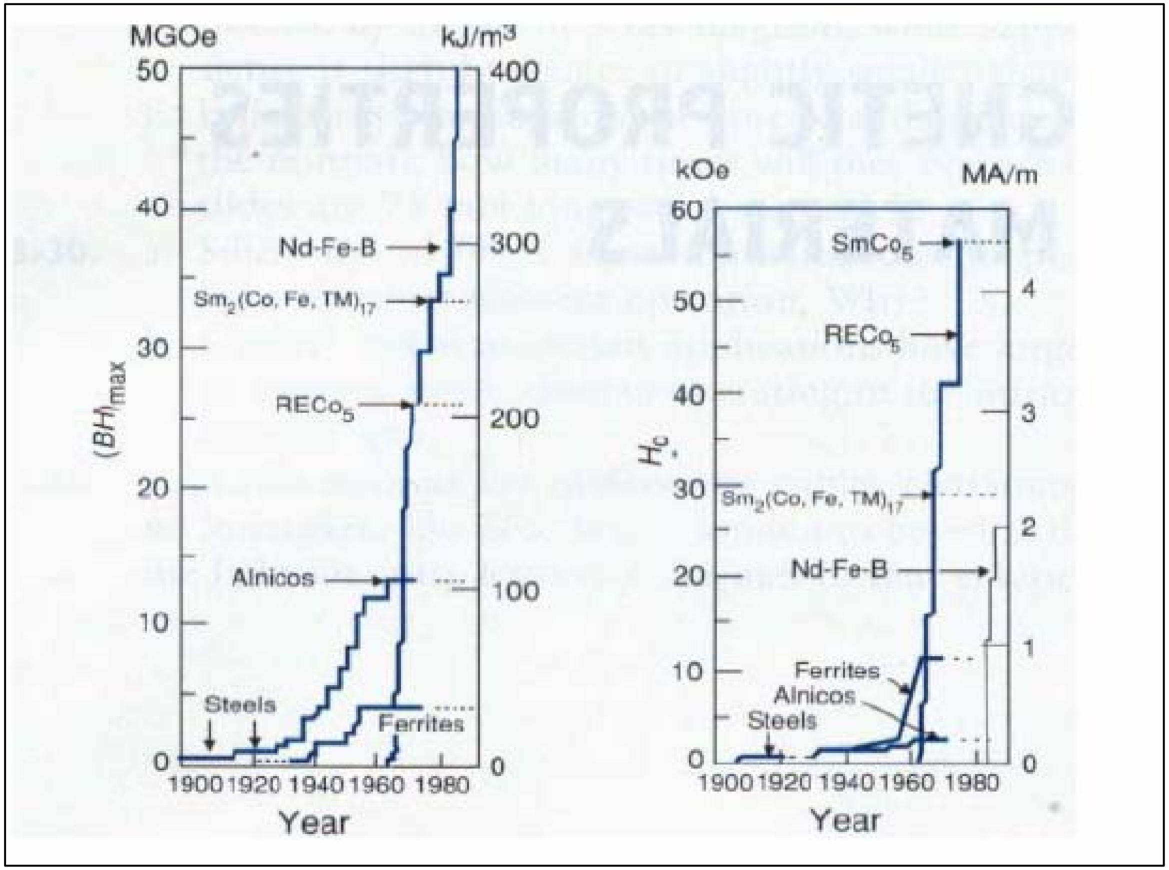
T.A. Edison, Pyromagnetic generator,
US patent 476,983, June 14, 1892.



Why would it work now?

Magnets over time: Strenght of the magnets (left) and coercitiv force/field (right)

National Materials Advisory Board, Report NMAB-426 on Magnetic Materials, 1985.



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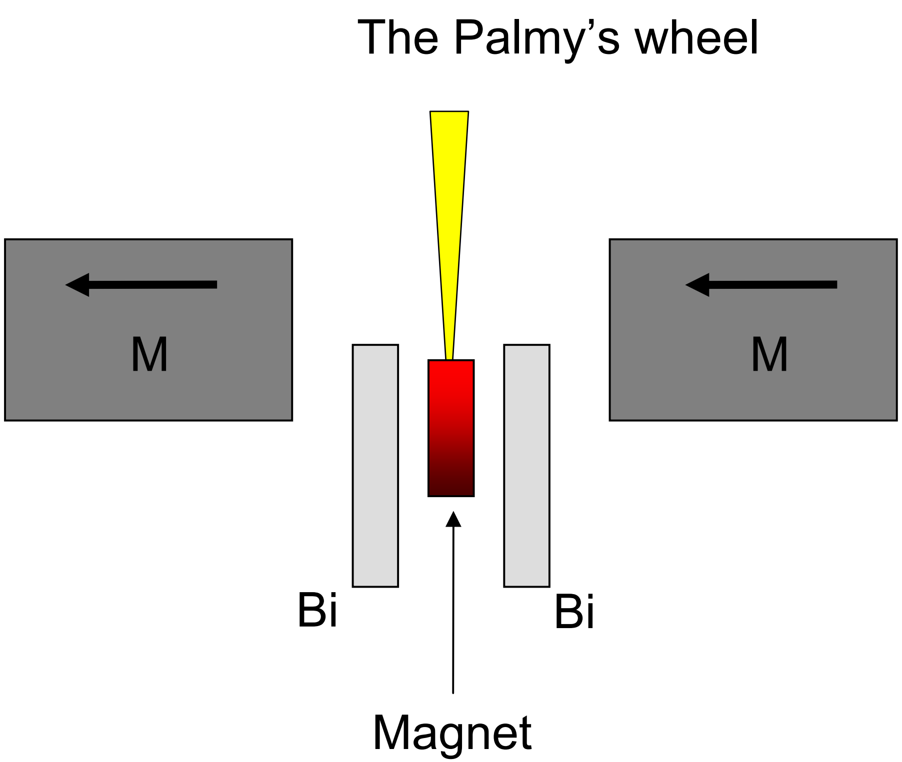
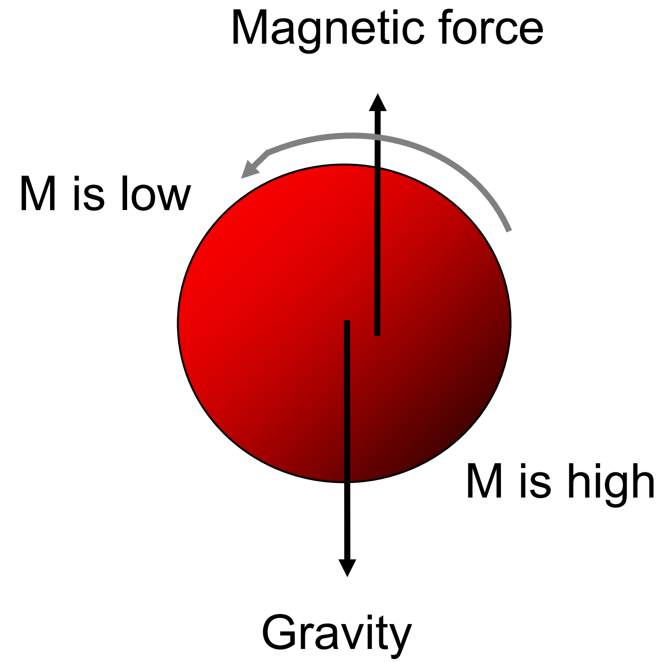
Another magnetic wheel





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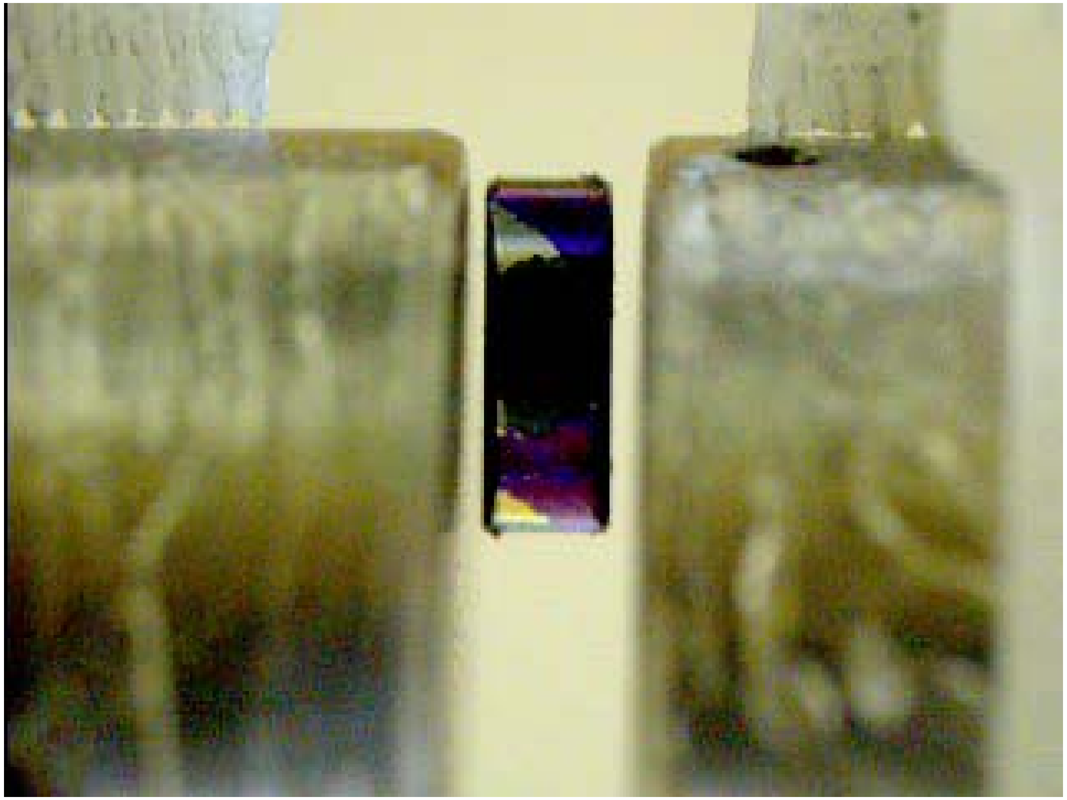
Palmy’s wheel



Experiment: Claudio Palmy, Swiss Alpine Institute, Stugl/Stuls, Switzerland

C. Palmy, A new thermo-magnetic wheel, Eur. J. Phys. **27**, 1289-1297, 2006.

Magnetic Cooling Working Party

Website:
www.mcwp.ch

Thank you for your attention