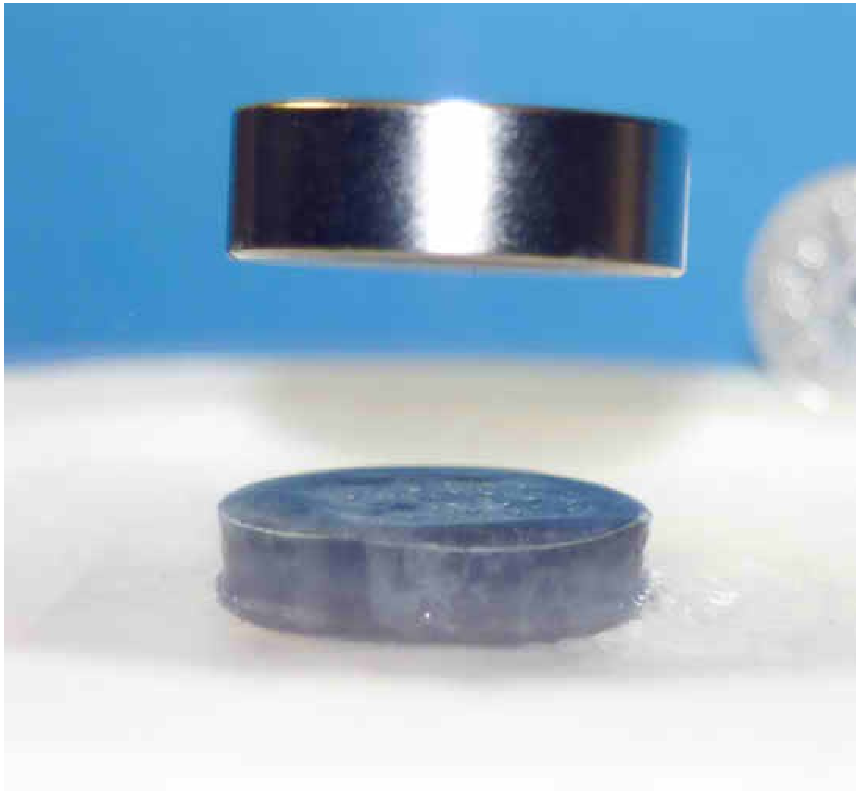
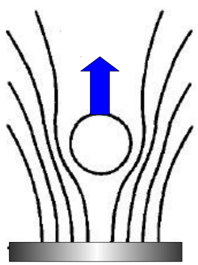
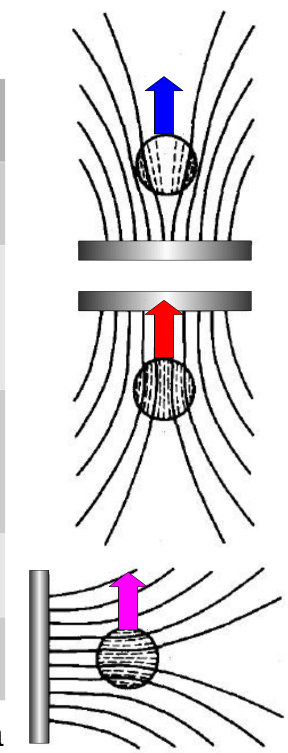
# Levitazione di Superconduttori nello stato misto

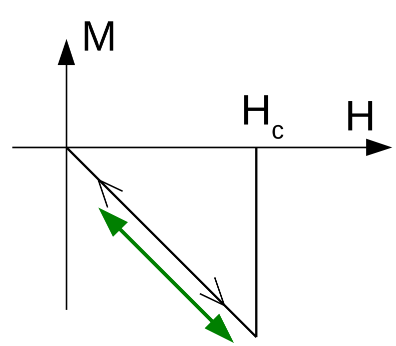
# Levitazione del “secondo tipo”

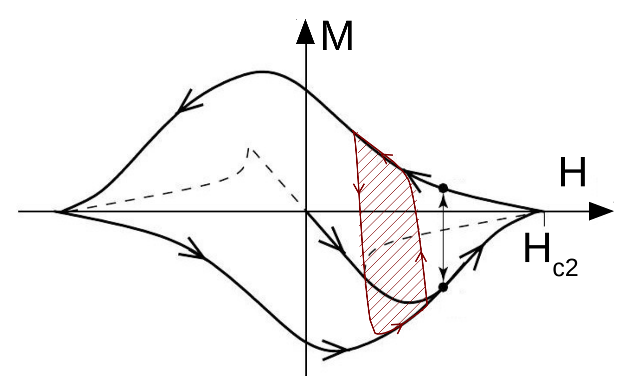


| stato | **Meissner** | **Misto con pinning** |
|---|---|---|
| azione a distanza | levitazione | levitazione/sospensione |
| interazione con magnete | repulsiva | repulsiva/attrattiva |
| risposta a perturbazioni | elastica | elastica/plastica |
| posizioni di equilibrio | unica | molteplici |
| equilibrio* | stabile | metastabile (decadimento) |



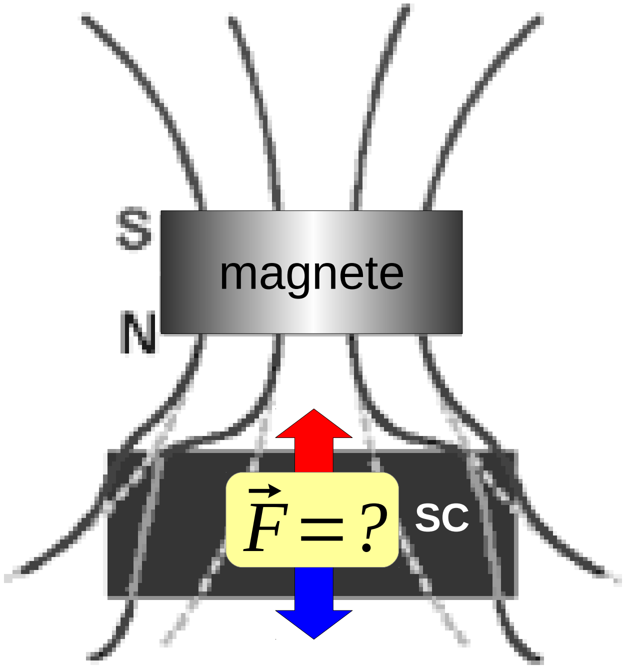
*Teorema di Earnshaw: stabilità impossibile con soli para-/ferromagneti in configurazione statica




Brandt, Appl. Phys. Lett. 53, 1554 (1988); Science 243 , 349 (1989); Am. J. Phys. 58, 43 (1990);

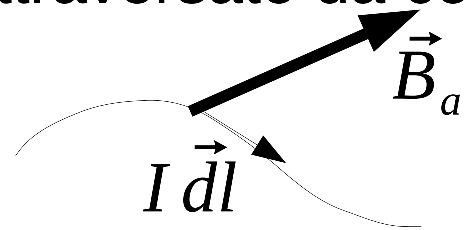
# Modello



# Azioni meccaniche in campo 1/2

- Forza su un circuito attraversato da corrente (2a legge di Laplace):

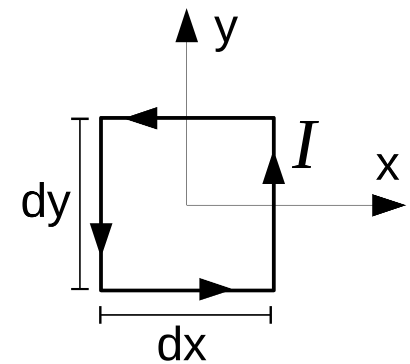
$$d\vec{F} = I\, d\vec{l} \times \vec{B}_a$$




$$\vec{F} = I \oint d\vec{l} \times \vec{B}_a$$

- Forza su spira elementare:

$$\vec{B}_a \| \vec{z} \qquad dF_x = I dy \left( B_z + \frac{\partial B_z}{\partial x} \right) - I\, dy\, B_z = I\, dx\, dy \frac{\partial B_z}{\partial x} = dm \frac{\partial B_z}{\partial x}$$




momento magnetico $\vec{m} = I\, S\, \hat{n}$ ⇒ $I\, dx\, dy = I\, dS = dm$

– sommando tutte le componenti:

$$d\vec{F} = (d\vec{m} \cdot \nabla)\, \vec{B}_a$$

- Forza su spira finita in campo $B_a$:

$$\vec{F} = (\vec{m} \cdot \nabla)\, \vec{B}_a$$

NB: forza≠0 per gradienti di $B_a$

# Azioni meccaniche in campo 2/2

- Forza su corpo magnetizzato:

$$\vec{F}=\int_V (\vec{m}\cdot\nabla)\vec{B}_a\,dV=\mu_0 V\left(\vec{M}(H)\cdot\nabla\right)\vec{H}_a$$

$\vec{M}=\frac{d\vec{m}}{dV}$ uniforme

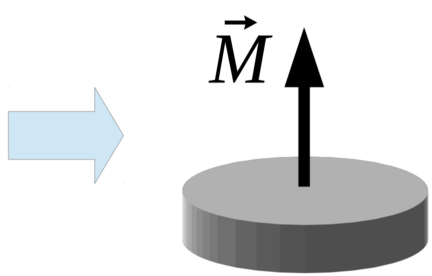
$\vec{B}_a=\mu_0\vec{H}_a$

Demagnetizzazione $H_a \neq H$:
$H_a$: applicato dall'esterno
H: interno

- Semplificando:

$H_a$ // asse principale

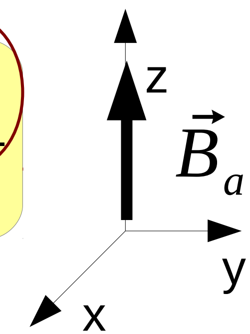
$H_a >> M \sim H_{c1}$




&

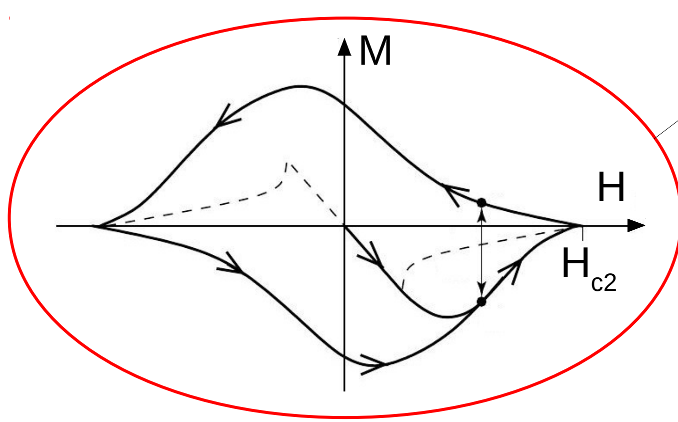
$\vec{F}\parallel\hat{z}\,,\quad F=\mu_0 V M(H_a)\frac{\partial H_a}{\partial z}$

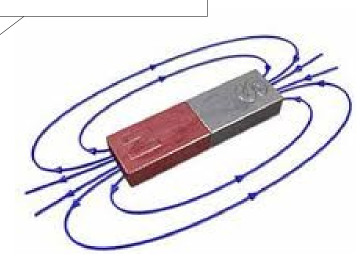
NB: SC massicci sono multigrano
→ $V_{eff}$ limitato da dimensioni grani



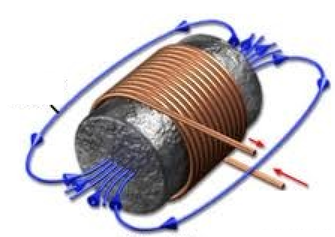

Risposta del SC

Eccitazione



magnete permanente

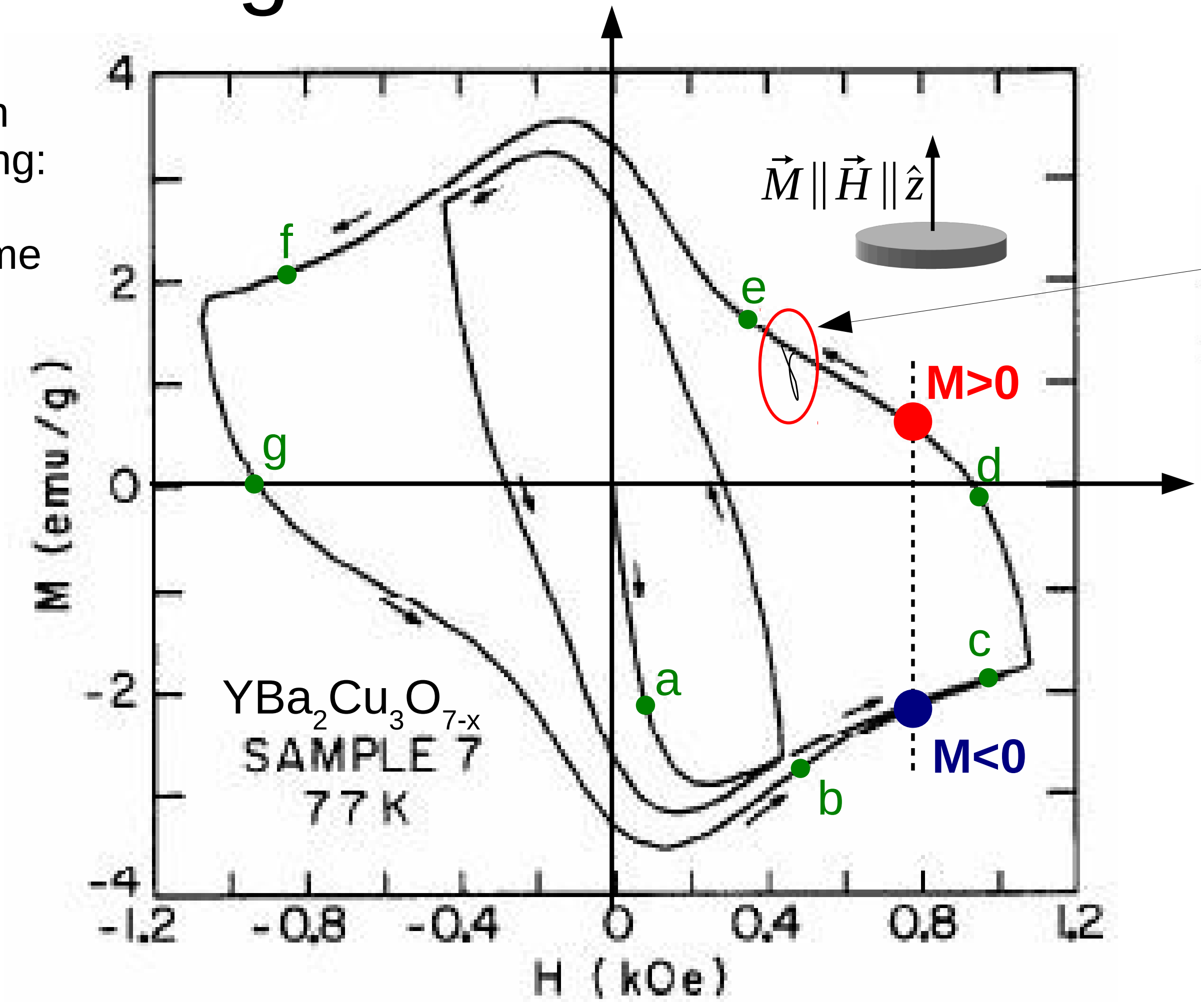


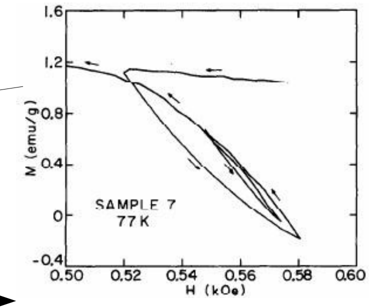
elettromagnete

# Ciclo di magnetizzazione e stato critico

Magnetizzazione di un SC di tipo II con pinning:

- B interno non uniforme
- irreversibilità (dissipazione)
- M(H) multivalore (dipende da storia)



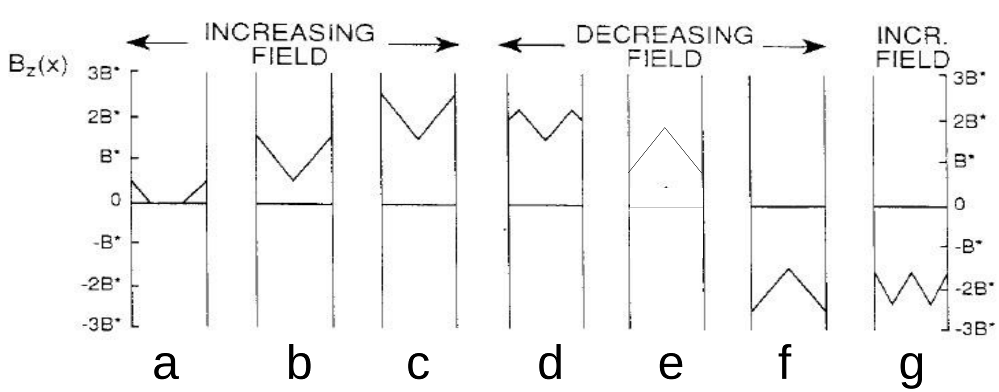

Shapira etal,
J. Mag. & Mag. Mat.
**78**, 19 (1989)

Modello di Bean:

- gradiente di B $\propto$ $J_c$
- disco di raggio r:

$$M_{sat} \approx \frac{J_c r}{3}$$

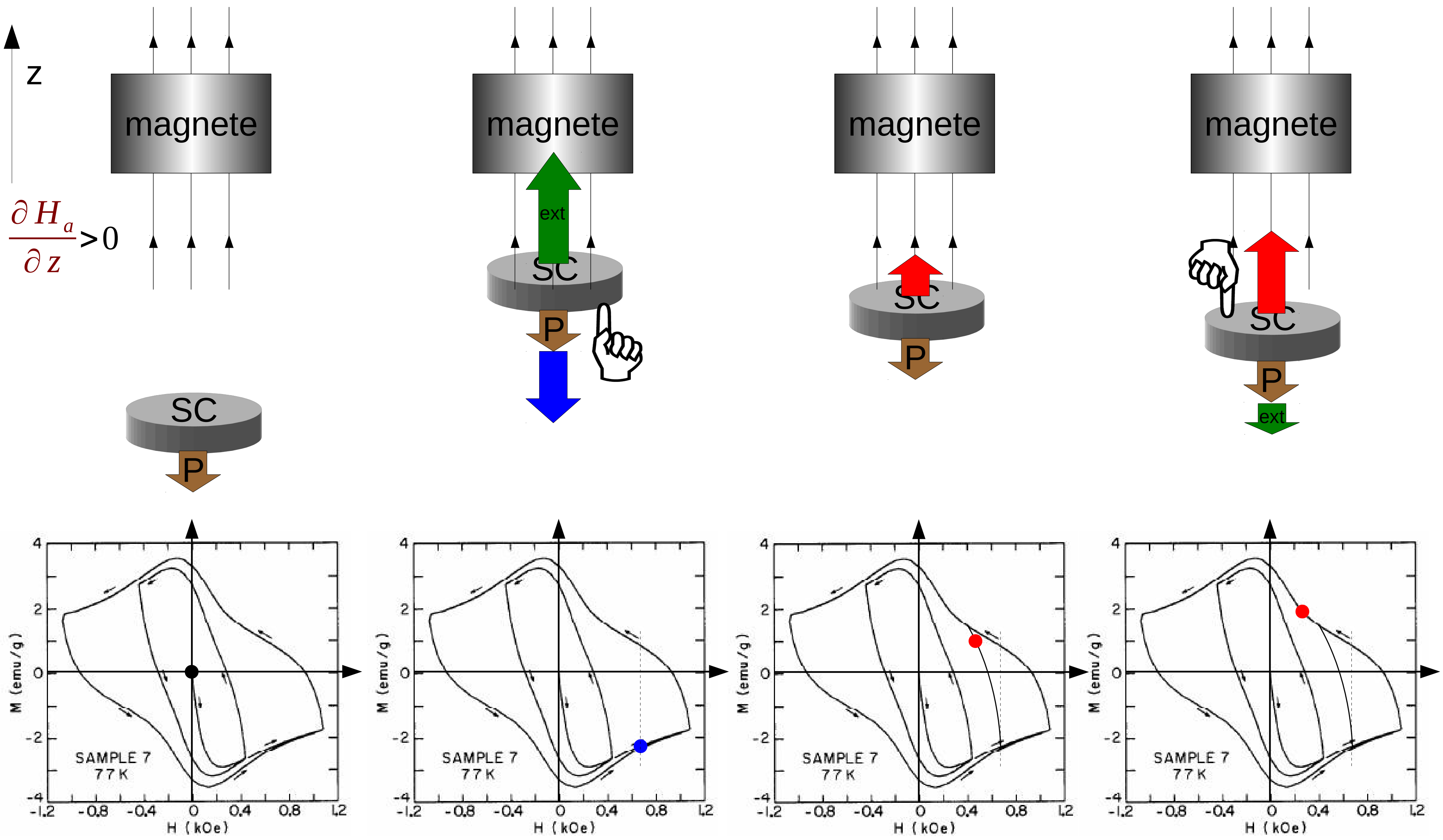
$$F \propto M \propto J_c$$




oss.: in generale $J_c = J_c(B)$

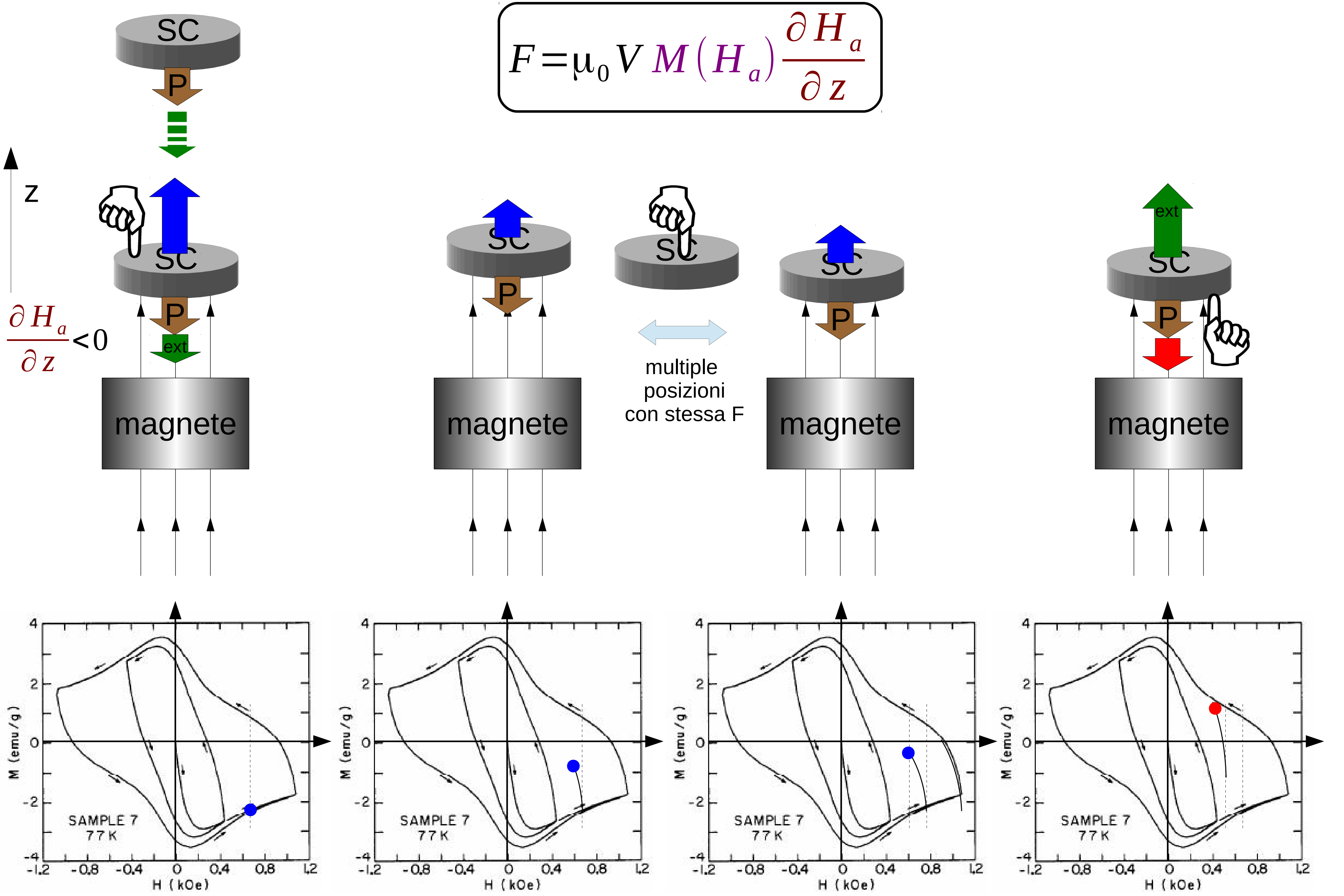
# Sospensione magnetica

$$F = \mu_0 V M(H_a) \frac{\partial H_a}{\partial z}$$

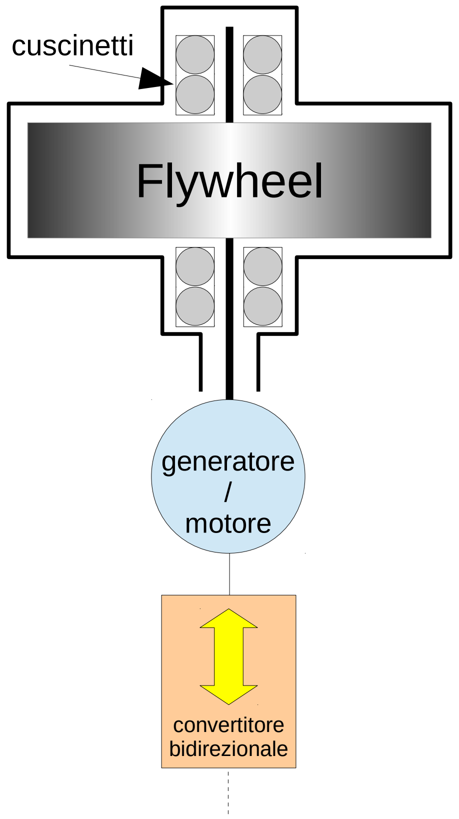


# Levitazione magnetica

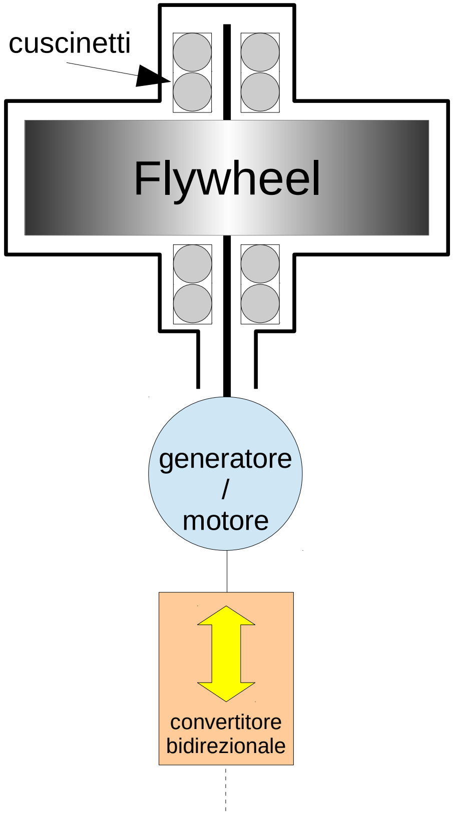
$$F = \mu_0 V\, M(H_a) \frac{\partial H_a}{\partial z}$$

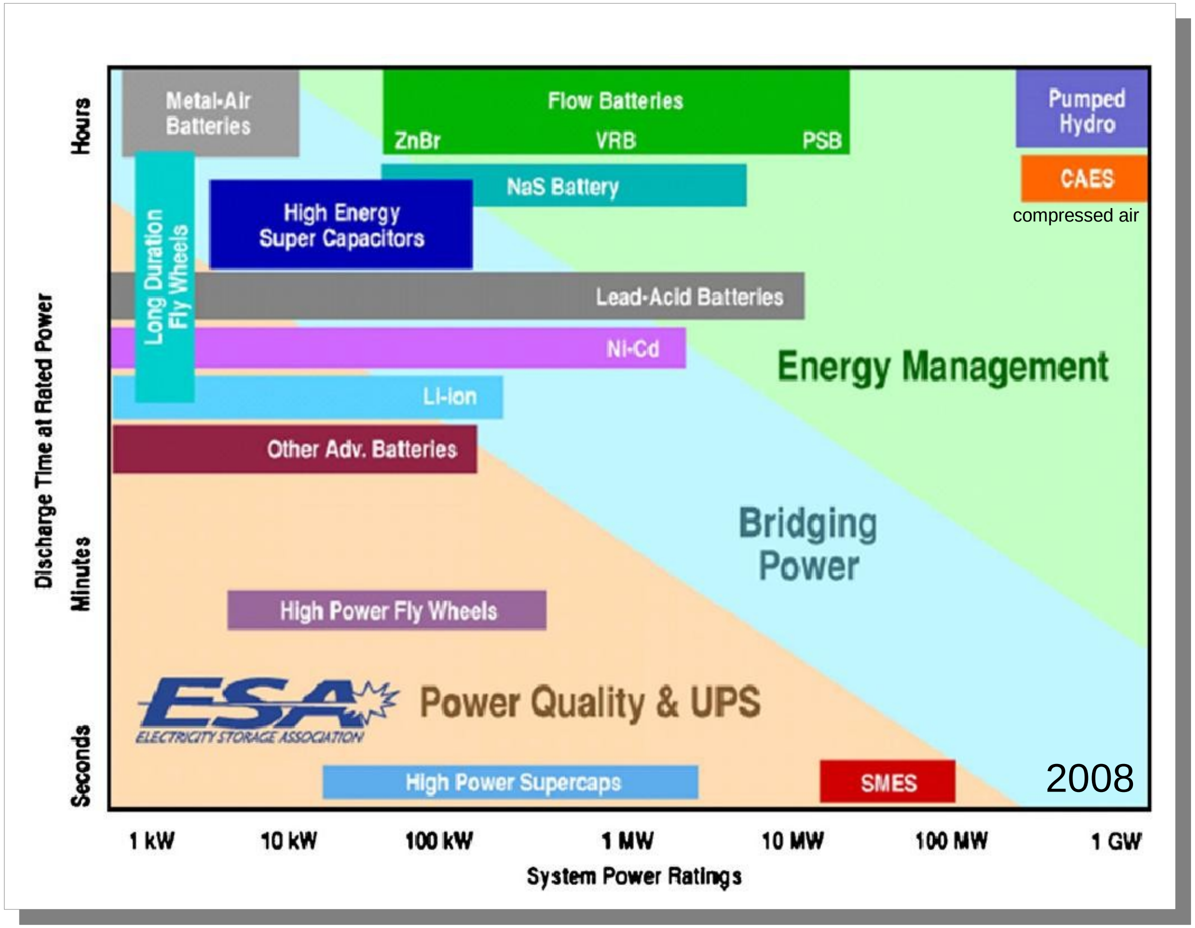


# Flywheels


cuscinetti
Flywheel
generatore
/
motore
convertitore
bidirezionale

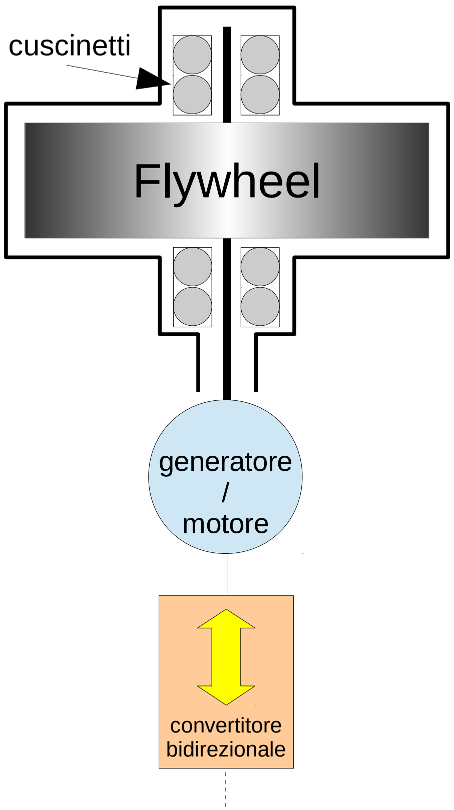
# Flywheels

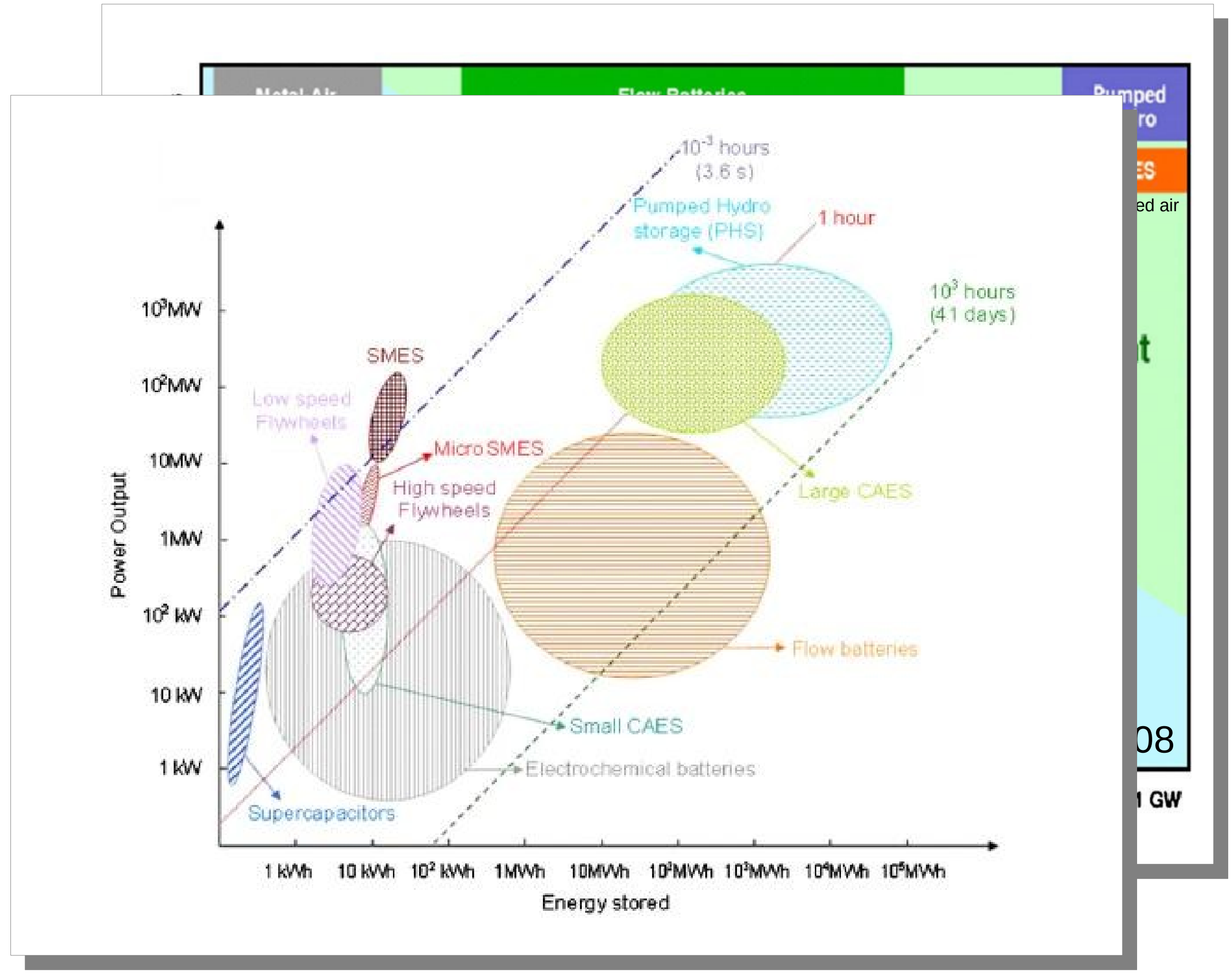



- brevi tempi di risposta, media potenza

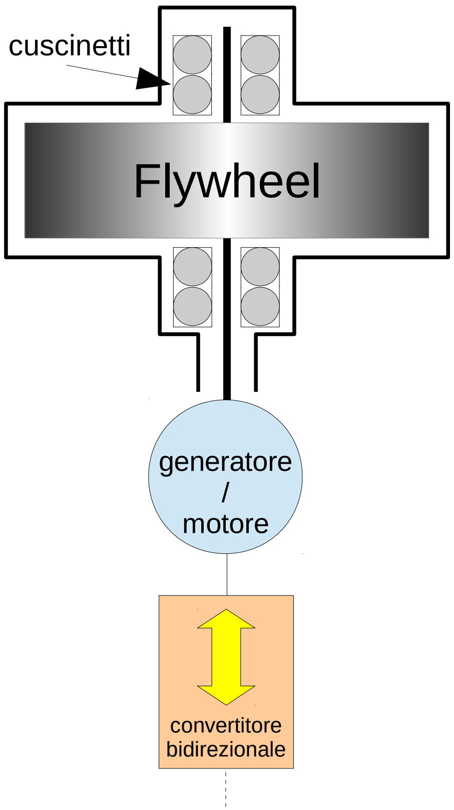
# Flywheels

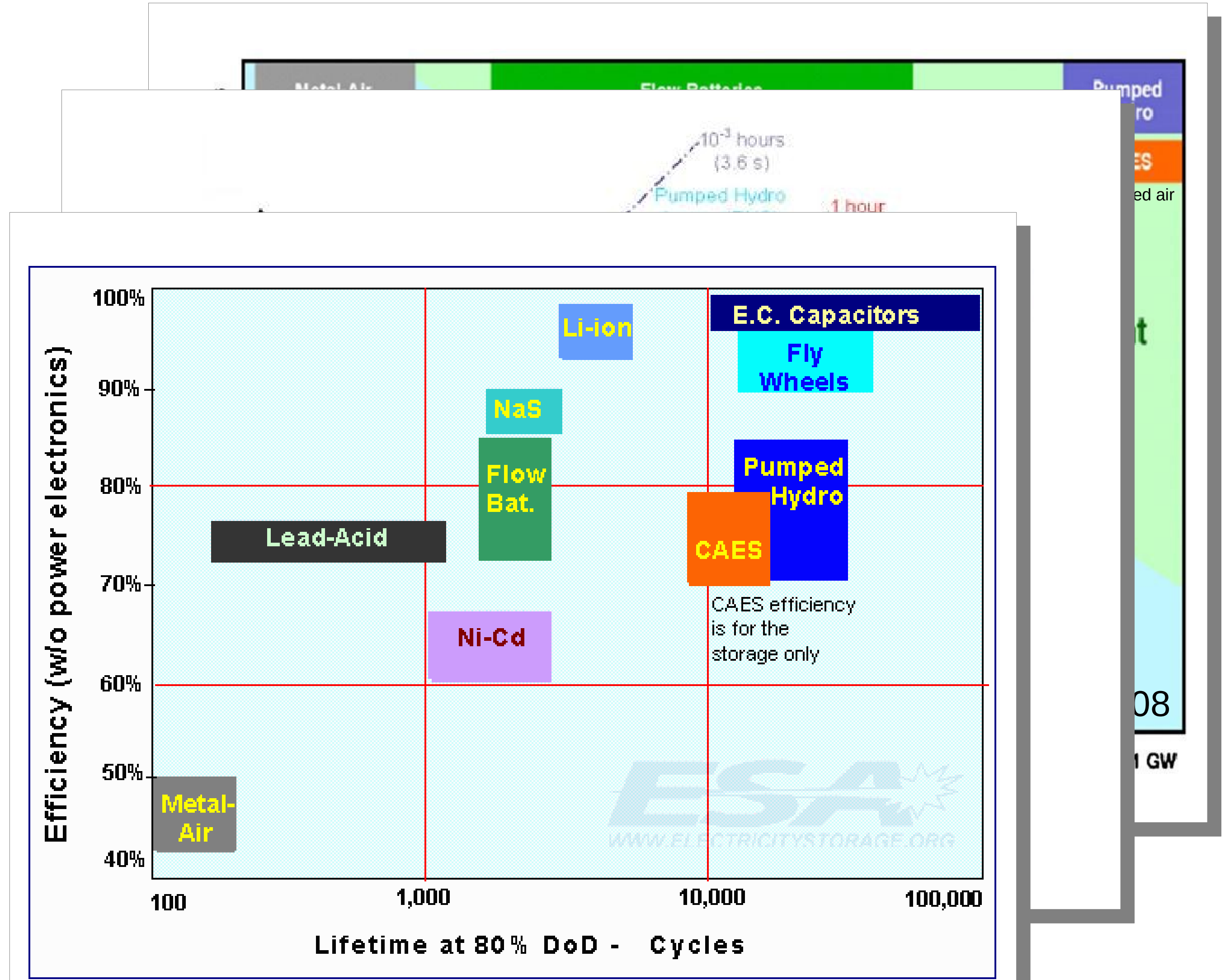



- brevi tempi di risposta, media potenza
- capacità media-bassa

# Flywheels




DoD: depth of discharge

- brevi tempi di risposta, media potenza
- capacità media-bassa
- alta efficienza, ciclo di vita esteso
- Applicazioni:
  - fornitura elettrica:
    gruppi di continuità, controllo qualità,
    associate a produzione elettrica distribuita
    (e.g. con fonti rinnovabili) (a)
  - altro: veicoli, anche come controllo (ACESF) di
    assetto combinato per v. aerospaziali (b)

(a) Toledo etal, Renew. & Sustain. Energy Rev. **14**, 506 (2010)
(b) Tang etal, Physica C **483**, 178 (2012)

# Flywheels – esempio di prodotto sul mercato

## *Flywheel*

from 60 to 900 kVA

Voltage Support Solution to ensure an autonomous static power supply


### The *Flywheel* advantages

Dynamic energy storage technology with even more technical advantages:

- outstanding reliability,
- reduced maintenance,
- simplified maintenance,
- long service life (> 20 years),
- max. power in min. volume,
- less floor space < 0,5 m$^2$,
- high efficiency 99.8 %,
- self-diagnostics,
- rapid recharging (configurable, up to 7 minutes),
- adjustable voltage and current parameters,
- silent operation,

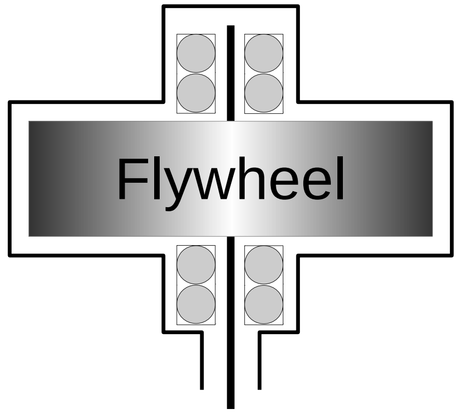
socomec
Innovative Power Solutions UPS

| | *Flywheel* | Battery |
|---|---|---|
| Operating costs | | |
| Energy consumption | very high efficiency energy | consumption to maintain, float charge |
| Maintenance | reduced | high |
| Ventilation - Air conditioning | not applicable | maintaining ambient temperature increases operating costs |
| Technical floor space | reduced | considerable, with ground loading constraints |
| Service life | high (> 20 years) | frequent replacements |
| Back-up time availability | | |
| Reliability | high | need for constant monitoring |
| Availability status | continuous | actual back-up time difficult to ascertain |
| Life cycle (number of discharges) | no impact on service life | reduces service life |
| Ambient temperature | no impact | reduced temperature range |
| Recharge time | very low (100 % in about 7 minutes) | high (80 % in about 8 hours) |

## Technical data

| | *Flywheel* |
|---|---|
| ELECTRICAL SPECIFICATIONS | |
| Rated unit power | up to: 190 kW / 12.5 seconds |
| Rated voltage (Input / output) | 600 V DC (adjustable) |
| Output voltage control | ± 1% under static conditions |
| Ripple factor | < 2% |
| Auxiliary voltage | 110 / 230 VAC |
| Auxiliary power | 400 VA |
| ENVIRONMENT | |
| Operating ambient temperature | - 20 °C to + 50 °C |
| Maximum altitude | up to 3000 metres |
| Acoustic level at 1 m (ISO 3746) | < 45 dBA |
| UPS CABINET | |
| Dimensions W x D x H | 630 x 830 x 1800 mm |
| Weight | 590 kg |
| Degree of protection | IP20 |
| Colours | cabinet: RAL 7012, door: silver grey |
| STANDARDS | |
| Conformity | CEE 73/23 Low voltage directive, CEE 98/037 Machine directive, IEC/EC 60439-1, IEC/EN 60204-1 Machine safety, EN 1127-1 Explosive atmospheres |

# Flywheels – componenti principali




Energia cinetica immagazzinata:

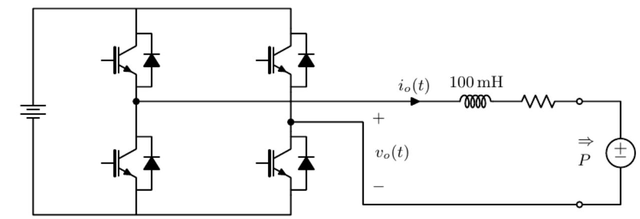
$$E_c = \frac{1}{2} I \omega^2$$

$$I = \int_V \rho r^2 dr^3$$

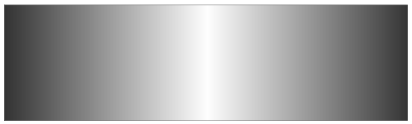
$$M = \int_V \rho \, dr^3$$

$$P = Mg \rightarrow F_{supporto}$$

M~100 Kg

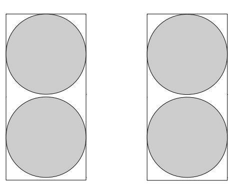



Elettronica di potenza + generatore/motore
conversione bidirezionale di energia elettrica in meccanica



materiale del rotore

$\omega_{max}$~20000 rpm



Cuscinetti (“bearings”):
- meccanici (alto attrito)
- magnetici
  - MP/MP (stab. attiva)
  - MP/SC (stab. passiva)
  - SC/SC

# Rotore

- ω limitata da rottura del materiale
- parametro: carico di rottura a trazione $\sigma_{\theta,u}$
- energia per unità di volume o massa:

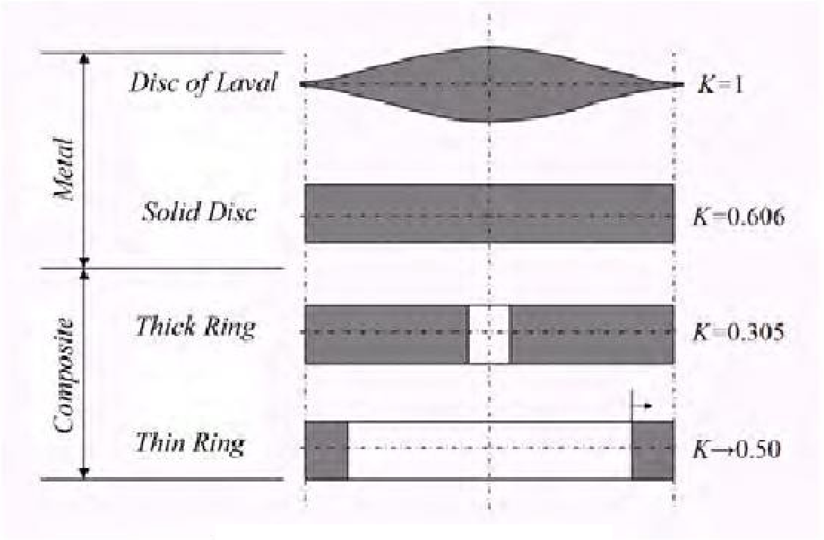
$$e_v = K\,\sigma_{\theta,u} \qquad e_m = K\,\frac{\sigma_{\theta,u}}{\rho}$$

→ $K$ legato alla forma del rotore:

TABLE II
CHARACTERISTICS FOR DIFFERENT FLYWHEEL MATERIALS [11].

| Material | $\rho$ [kg/m$^3$] | $\sigma_{\theta,u}$ [MPa] | $e_v$ [MJ/m$^3$] | $e_m$ [kJ/kg] |
|---|---|---|---|---|
| Aluminum | 2700 | 500 | 251 | 93 |
| Steel | 7800 | 800 | 399 | 51 |
| Glass E/Epoxy | 2000 | 1000 | 500 | 250 |
| Graphite HM/Epoxy | 1580 | 750 | 374 | 237 |
| Graphite HS/Epoxy | 1600 | 1500 | 752 | 470 |

confronto metalli e materiali compositi



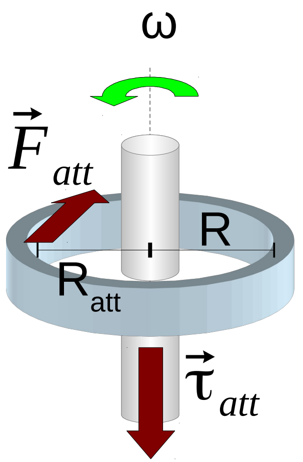

forme del rotore

R. Peña-Alzola etal, Proc. of the Int. Conf. on Power Eng., Energy and Electrical Drives (2011)
F.J.M. Thoolen, PhD thesis (1993)

# Cuscinetti

- Parametri di progetto principali:
  - carico statico – forza di sollevamento

$$P = Mg = F_{cuscinetti}$$




  - perdite per attrito. Coefficiente di attrito: $\mu = F_{att}/P$

$$\tau_{att} = F_{att} R_{att} = -I\dot{\omega}$$

$$I = M R^2$$

$$\mu = |(\dot{\omega})| \frac{R^2}{g R_{att}} \qquad \frac{\dot{E}}{E} = -\frac{2\mu g}{\omega R}$$

  - Con $\omega R_{eff} \geq 1000$ m/s e perdite desiderate $|\dot{E}/E| \leqslant 0.1\,\%/h$ → $\mu \leqslant 10^{-5}$

    Cuscinetti a sfera: $\mu \geqslant 10^{-3}$ ✗ → **Sospensione magnetica** ✓

    senza contatti meccanici + sistemi in vuoto → attriti~0

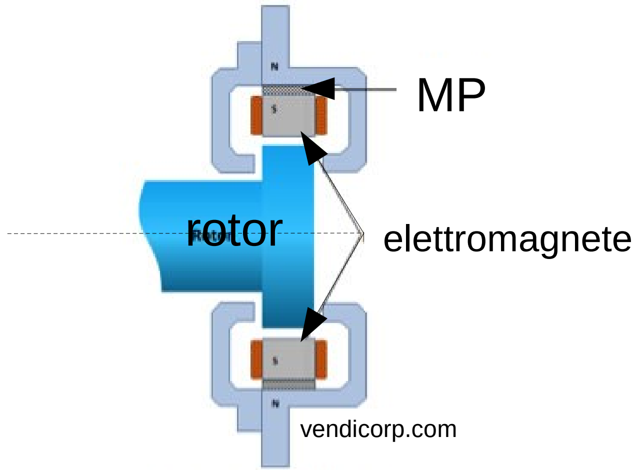
  - rigidità (“stiffness”) a fronte di piccoli spostamenti/disallineamenti

  - non linearità (instabilità dinamiche)

Hull etal, IEEE Trans. Appl. Supercond. **5**, 626 (1995)

# Sospensione magnetica

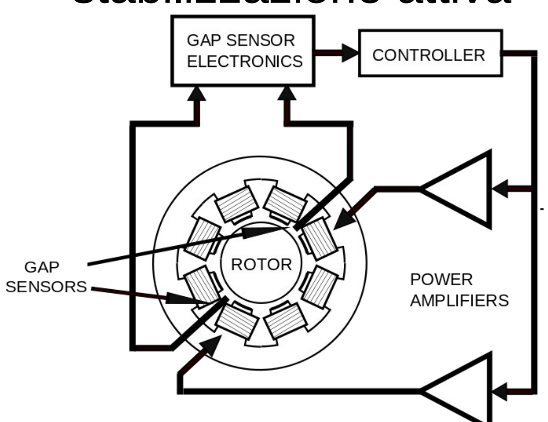
- Magneti permanenti (MP)




Cross-section of axial bearing

  - intrinsecamente instabile (teo. di Earnshaw)

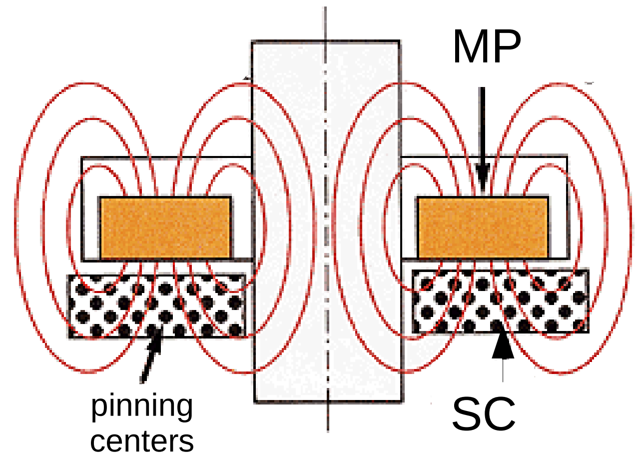
stabilizzazione attiva




Dissipazione: elettronica+elettromagneti ✗

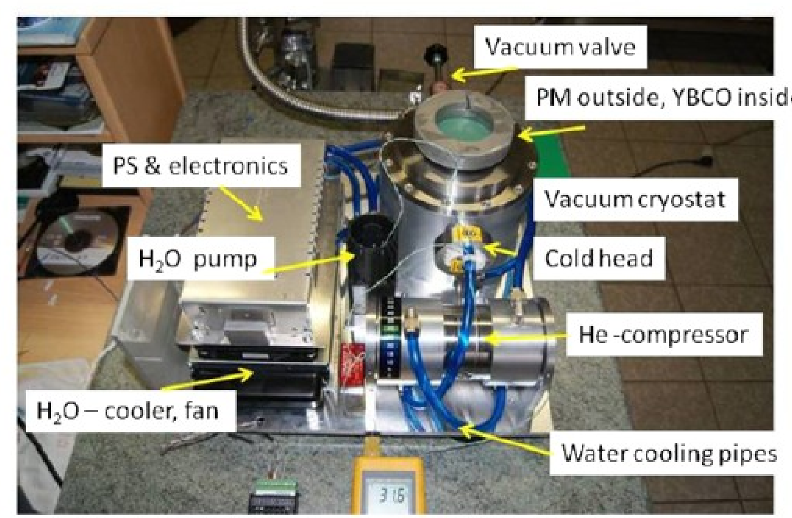
$$\mu \sim 10^{-4}$$

- Superconduttori (SC) di tipo II




  - intrinsecamente stabile ✓
  - $T<T_c$ → sistema criogenico

HTS magnetic platform with Stirling – cooler AIM SL400 B




Werfel etal, SUST **25**, 014007 (2012)

WTEC Panel Report on "Power Applications of Superconductivity in Japan and Germany" (1997)

# Sospensione magnetica a superconduttore (SMB)

- forza di sollevamento ("levitation pressure"): 2-10 N/cm$^{-2}$ (~1 Kg per cm$^2$)
  - strategie per incrementare il carico:

aumentare Jc:
- incremento del pinning (ingegneria dei materiali)
- riduzione di T, ma consumi di criogenia ↑↑

soluzioni ibride

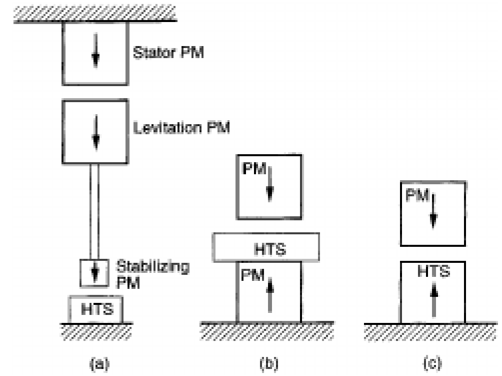
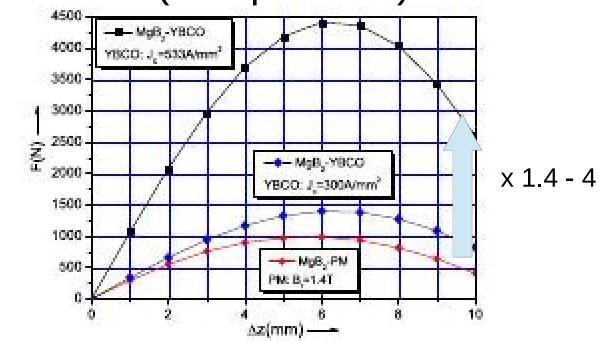



**Figure 7.** Magnetic biasing methods to improve the levitational pressure in HTS bearings: (a) Evershed-type design with attractive-force augmentation, (b) repulsive-force augmentation and (c) trapped-field augmentation.

$H_{sat}$~ 1-1.5 T del MP
→ sostituire MP con elettromag. a SC (complesso..)

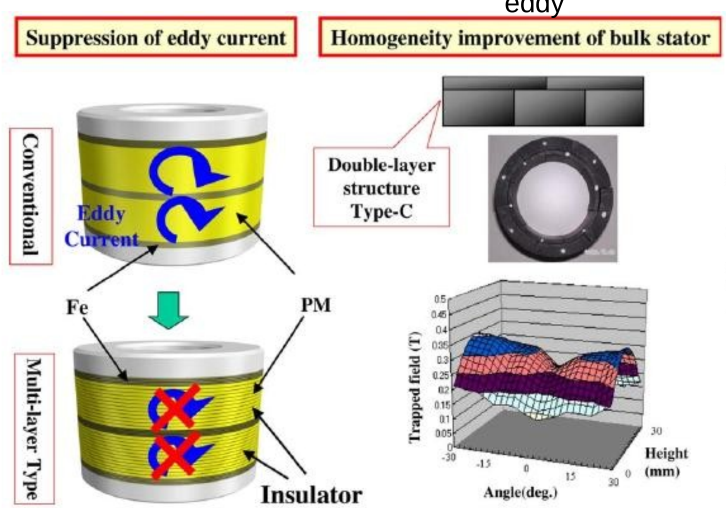



Patel etal, SUST **24** 015009 (2011)

- Perdite: $\mu \sim 10^{-7}$ + criogenia → $\mu \sim 2 \cdot 10^{-6}$

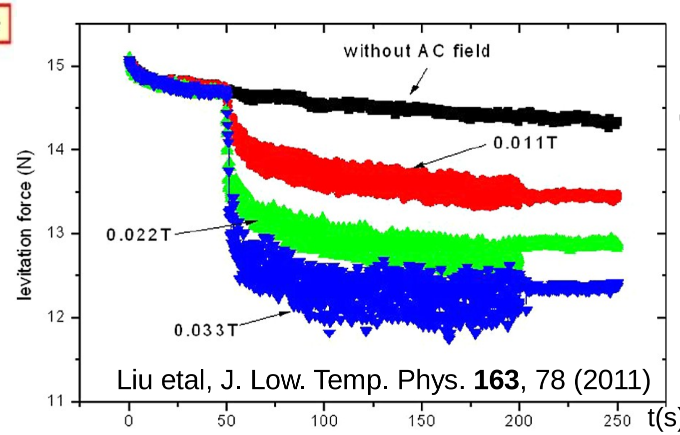
dissipazioni dovute a:

- H non uniforme → $J_{eddy}$



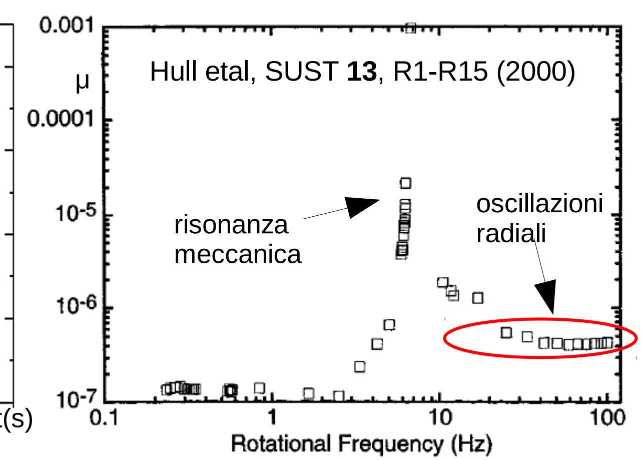

Koshizuka, Physica C **445-448**, 1103 (2006)

- moto flussonico; creep:



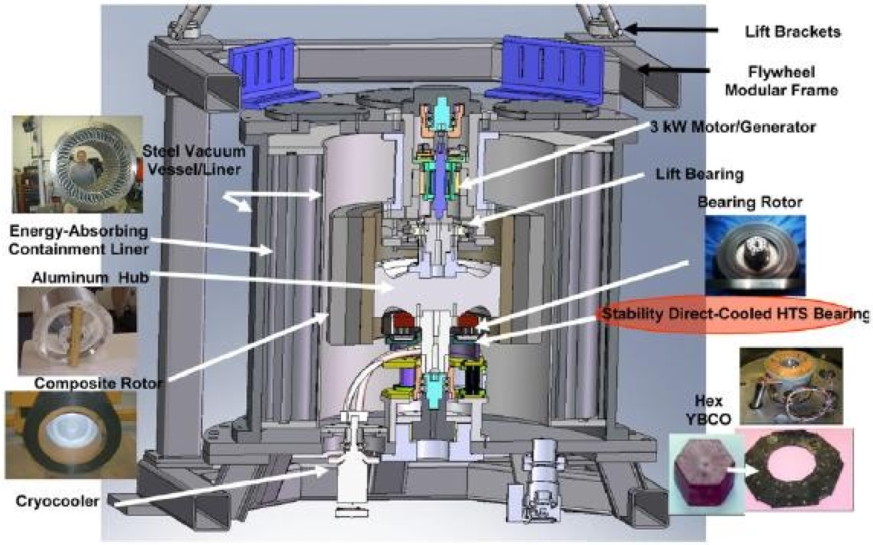

decadimento della forza dovuto a creep (misure su YBCO massiccio raffreddato in zero campo)

- instabilità dinamiche

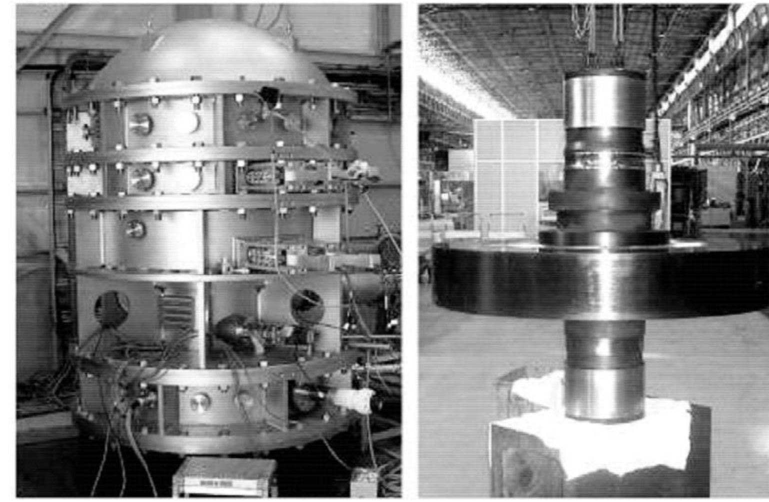



disco di MP (dia=25.4 mm, h=9.6 mm) sospeso 10 mm sopra un cilindro di YBCO

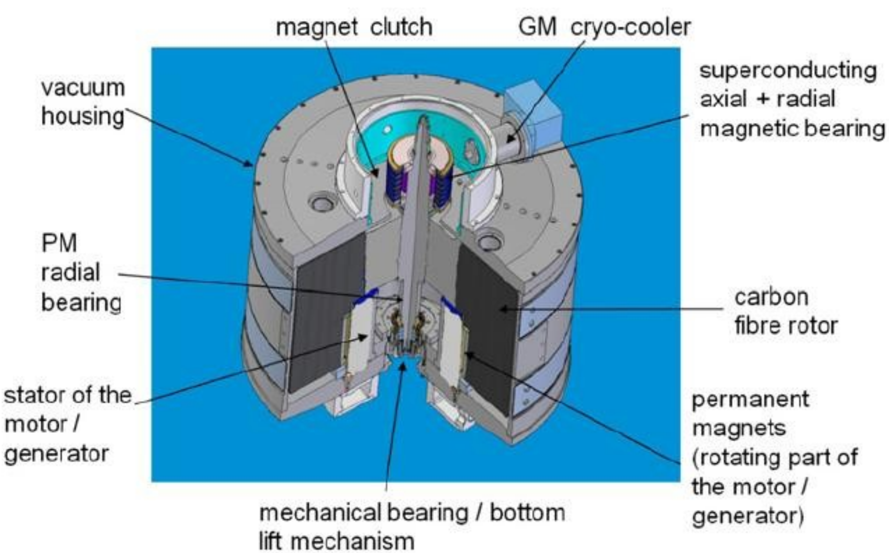
# Prototipi di flywheel a SC




Boeing, 5 KWh/ 3 KW, 164 Kg rotor



NEDO, 5 KWh, 11000 rpm, 125 Kg rotor




ATZ/MM, 2 KWh/250 KW

**Table 2.** R&D development costs of HTS flywheels.

| Institution/project | (million US $) |
|---|---|
| Boeing, USA | ~20 |
| NEDO consort. JP | ~35 |
| Nexans & Piller, GER | ~10 |
| Kepri project, KR | ~14 |
| ATZ/MM, GER | ~2.3 |
| NEDO, LTS, JP | ~25 |

Werfel etal, SUST **25**, 014007 (2012)