Development of Improved Powder for Bonded Permanent Magnets

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FreedomCAR

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FreedomCAR Goals for 2015 Require Technology Breakthroughs and High Production Volumes

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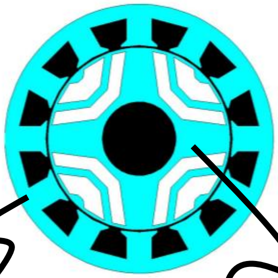
Advanced IPM design and high temp. magnets → Complex magnet shape & air cooling can boost efficiency

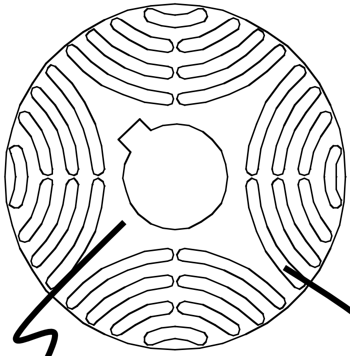
55kW (peak) PEEM System	200,000 units Cost < $660

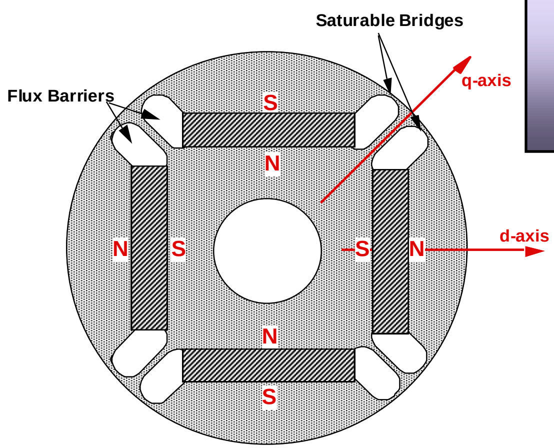
→ Power Electronics

→ Electric Machine

- → Motor Stator
- → Interior PM Rotor (e.g.,internal PM)
  - → Iron Core: Flux carrier, Soft magnet
  - → Permanent Magnets: Flux source, 30% of motor cost; Manufacturing cost, 40% targeted







Interior PM (IPM) machine is FreedomCAR focus

Project Objectives:

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- Develop high performance permanent magnets (PM) for traction motor with internal PM rotor :
  - requires elevated temperature (180-200˚C) operation, minimize cooling needs
  - increased high temperature magnetic performance more critical than RT

- Reduce manufacturing cost of PM traction motors:
  - bonded PM can utilize injection or compression molding technology
    - net shape forming for mass production of rotors

- Achieve high performance and reliability for bonded magnets:
  - increase volumetric loading
  - minimize irreversible magnetic losses (oxidation)

Sintered vs. Bonded (RSP) RE-Fe-B (2-14-1) Permanent Magnets

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Sintered

Cast/homogenized/crushed/pressed/sintered

Anisotropic (Aligned)

crystallographic

magnetic

- Plus:

  -high energy product

- Minus:

  -magnetize each part

  -difficult assembly of segments

  -corrosion (plate each part)

Bonded

RSP: Melt spun (flake), Atomized (spherical)

Crystallization annealed/compounded/formed

Isotropic (Microcrystalline)

- Plus:

  -net shape molding (full assemblies)

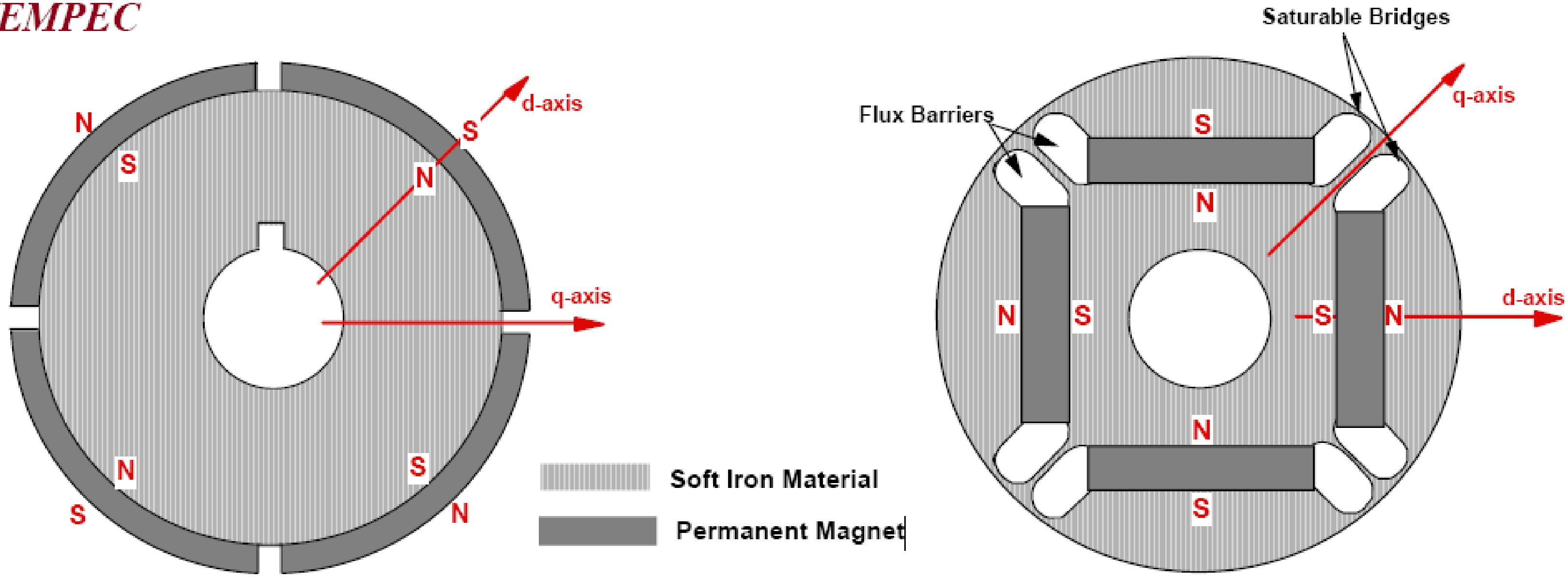
  -magnetize assembly (multi-sector)

  -corrosion resistance (encapsulated)

- Minus:

  -reduced energy product

PM Synchronous Machine Types

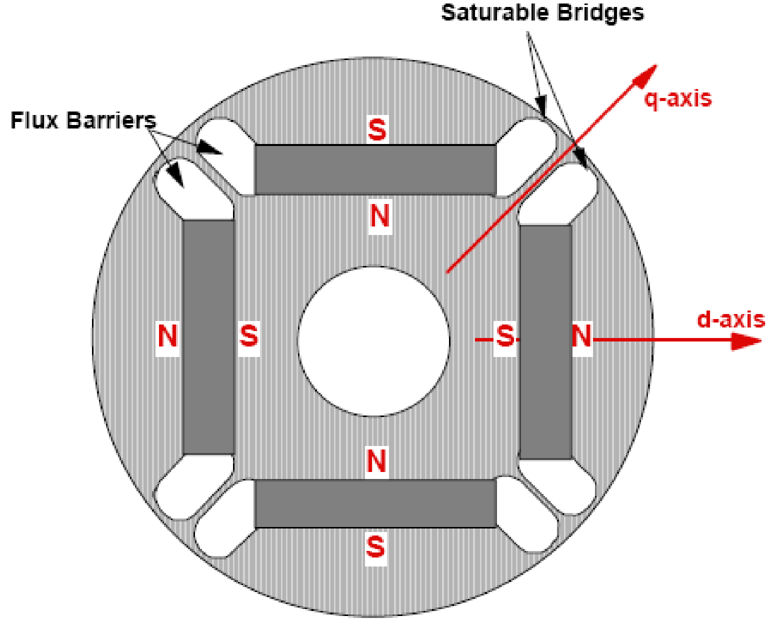


Surface PM   *Interior PM*

- Surface PM machines are dominant class of PM machines in world today
- Interior PM machines bury magnets inside rotor, creating a salient-pole synchronous machine

WEMPEC
Tom Jahns, U of Wisc

IPM Machine Torque Production



$$T_e = \frac{3}{2} p \left[\Psi_m i_q - \left(L_q - L_d \right) i_q i_d \right]$$

Magnet Torque

Reluctance Torque

Tom Jahns, U of Wisc

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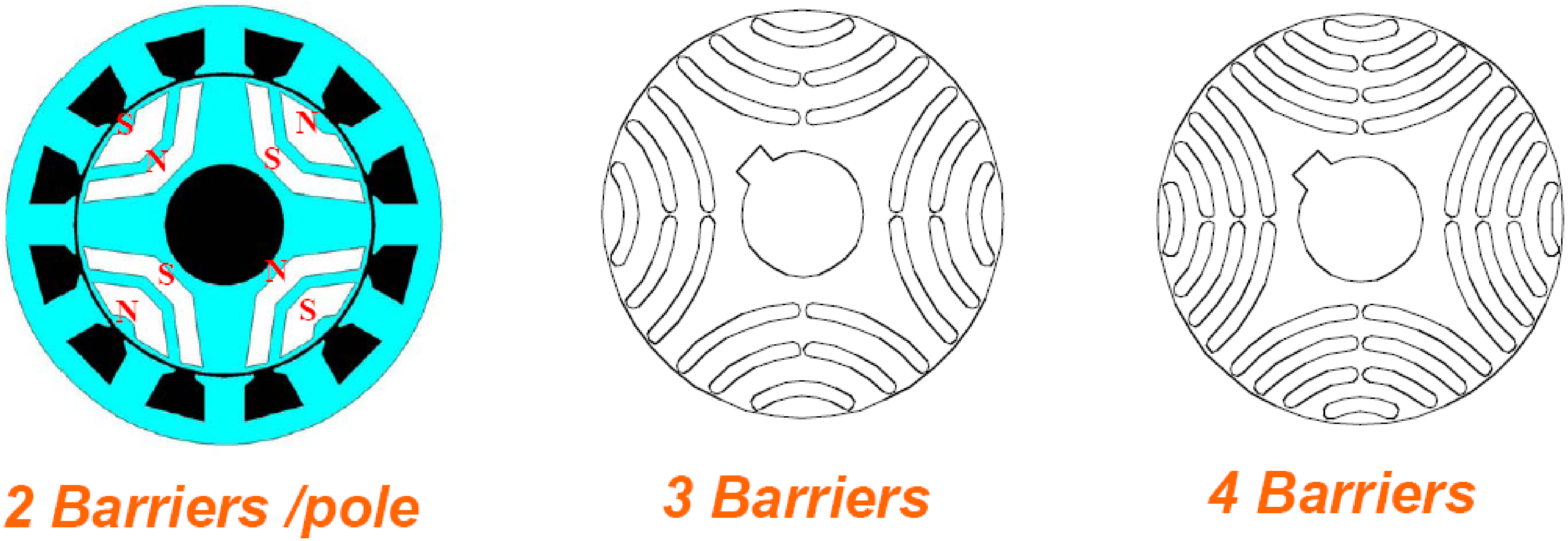
Multi-Barrier IPM Rotors



- Baseline design can be extended to include multiple barriers per pole
- Saliency ratio increases with number of barriers-per-pole
  - Reach point of diminishing returns with 3 or 4 per pole

Magnet Production Techniques

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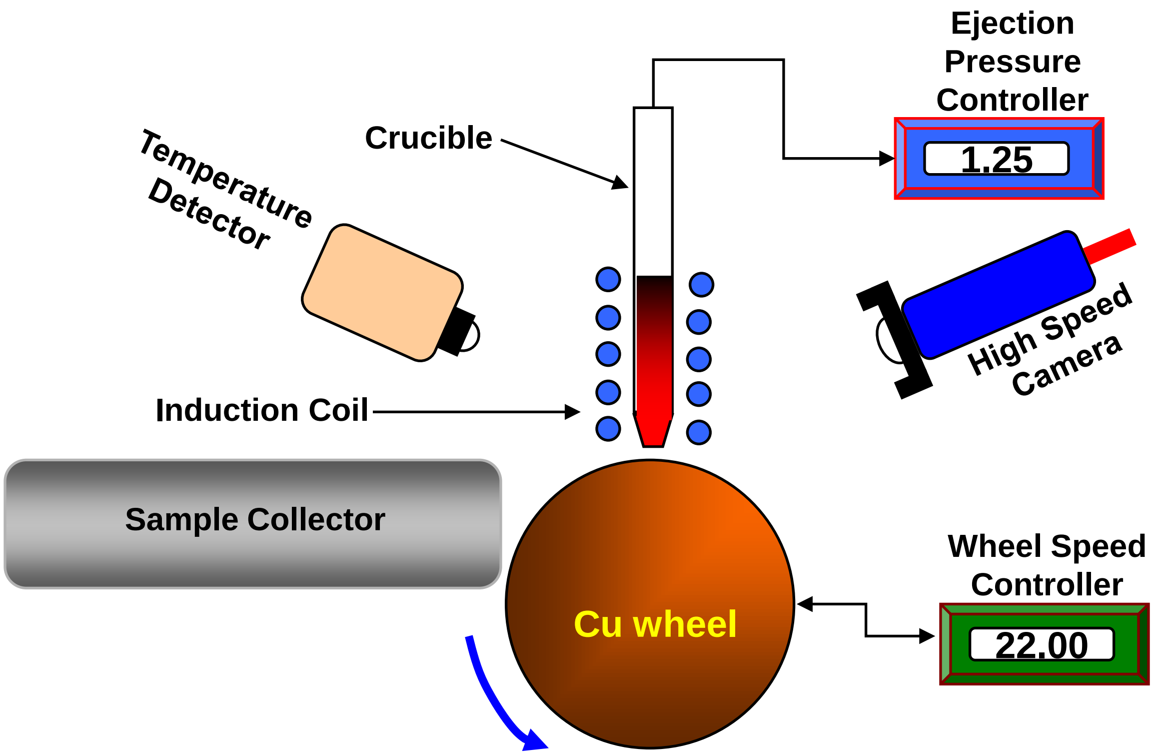
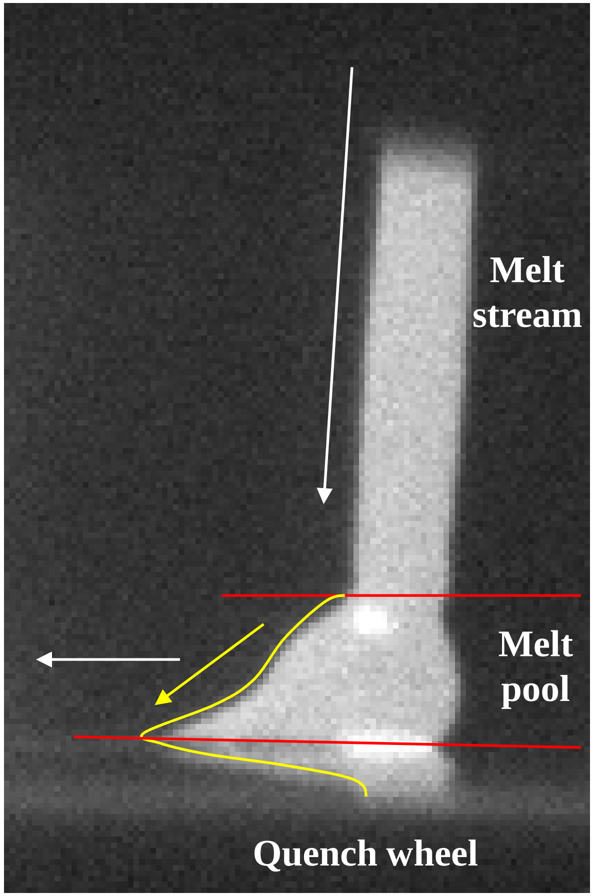
Melt Spinning Technique





Gas Atomization of Spherical Powder

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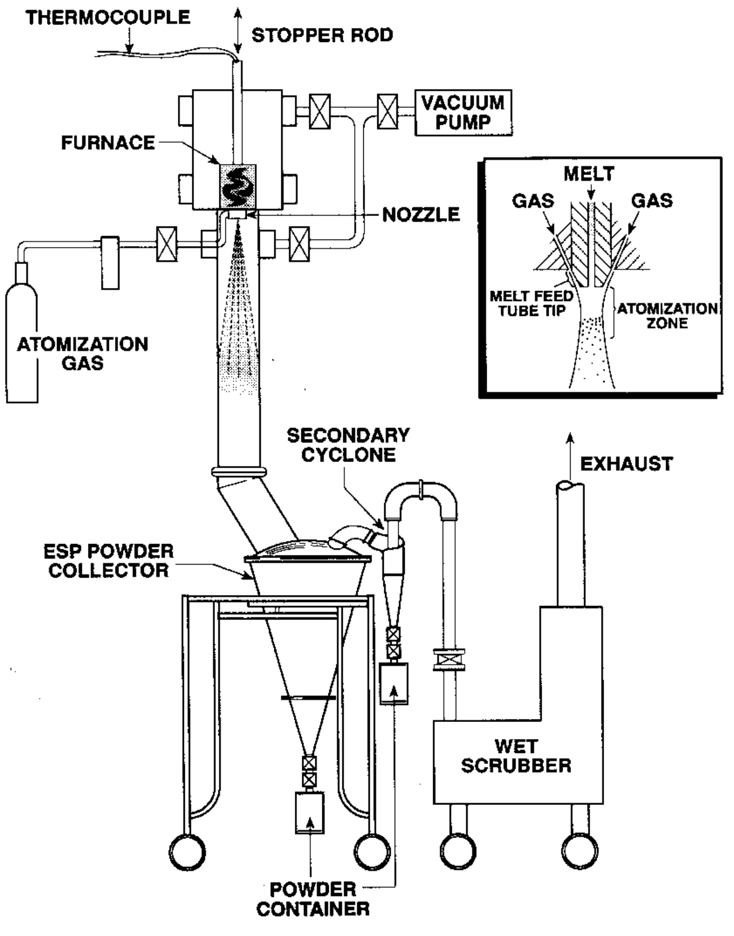

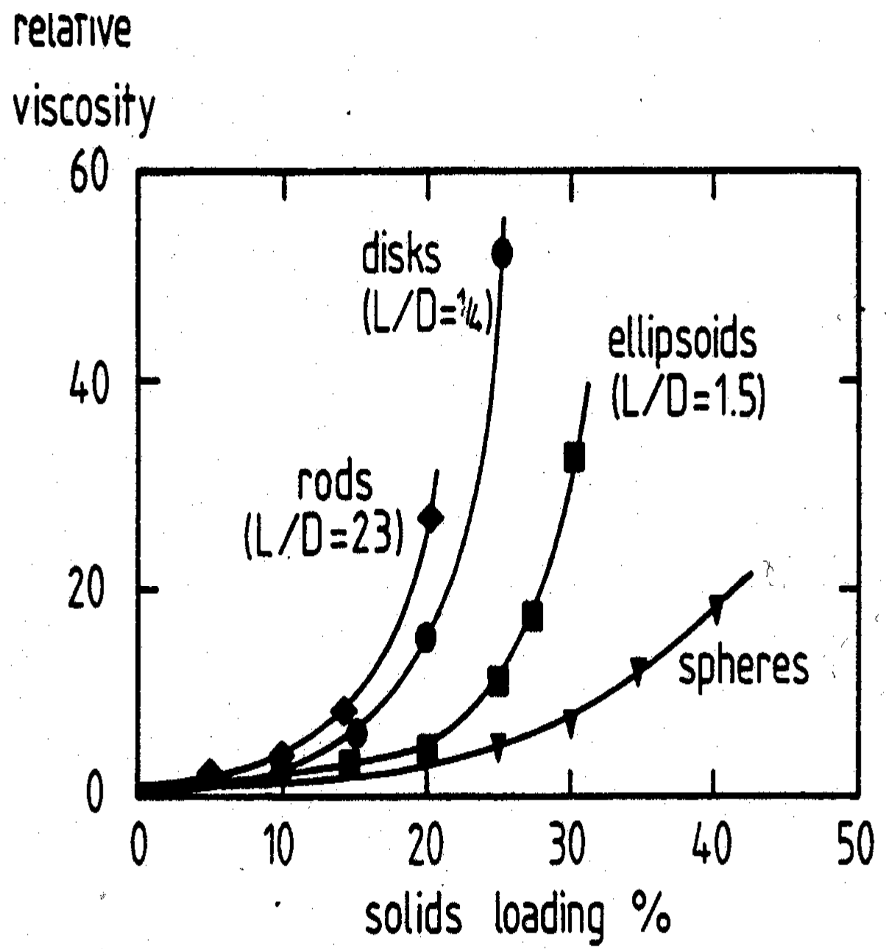

Alloy Design

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$Nd_2Fe_{14}B$

- Plus
  - Nd
    - relatively abundant RE
    - large magnetic moment
    - low vapor pressure
    - reactivity not bad
  - High saturation magnetization
- Minus
  - low Curie temperature
  - large temperature dependence of the magnetocrystalline anisotropy
  - peritectic compound
    - difficult to form pure compound
    - In equilibrium with a low melting liquid

Pseudo-conservation of mediocrity

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- Given the qualities
  - Magnetic
    - T_c, B_r, α, H_{ci}, β, BH_{max}
  - Physical
    - Ductility, toughness, hardness
  - Financial
    - Cost, ease of assembly
- The sum is essentially constant

What are the factors that determine B_r?

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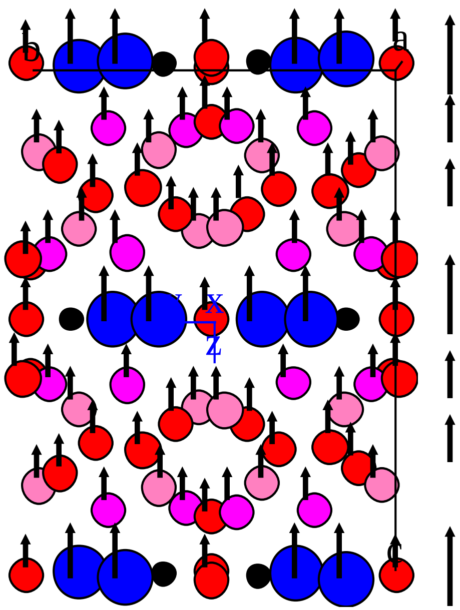
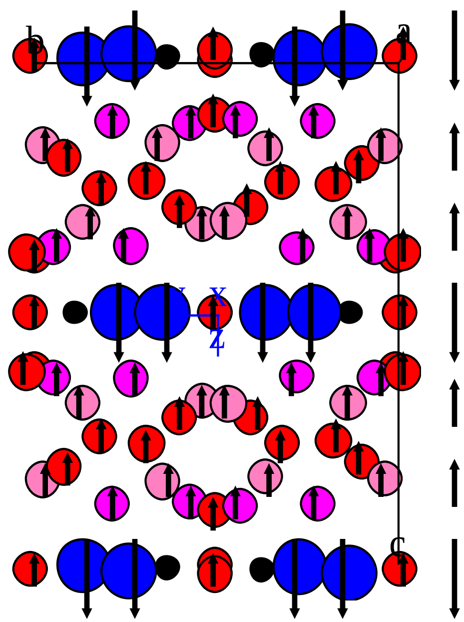
- Magnetic moment of the hard phase
  - $Nd_2Fe_{14}B$
    - Nd=3.3 μ_B/atom, Fe~2 μ_B/atom
    - Ferromagnetic coupling
    - ~35 μ_B/formula unit
  - $Dy_2Fe_{14}B$
    - Dy=10μ_B/atom, Fe~2 μ_B/atom
    - Antiferromagnetic coupling
    - ~8 μ_B/formula unit
- Degree of orientation of the hard phase
- Volume percent of the hard phase

Alloy Design

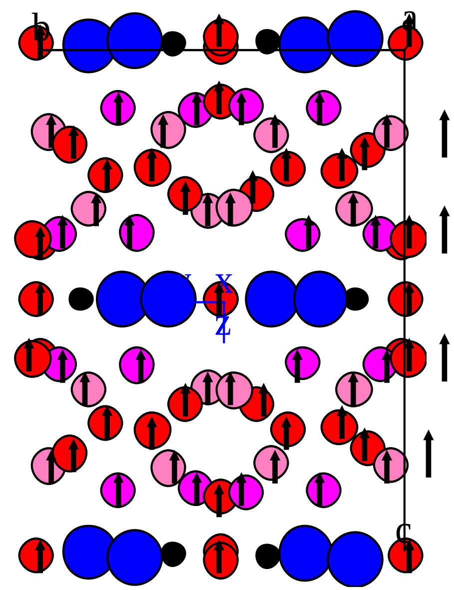
$Nd_2Fe_{14}B$



$Dy_2Fe_{14}B$



$Y_2Fe_{14}B$



Alloy SUMMARY

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- YDy-based $[Nd_x(YDy)_{0.5(1-x)}]_{2.2}Fe_{14-y}Co_yB$
  - compensate the loss of M_s and H_{cj} due to heating
  - simultaneously yield smaller temperature coefficient of B_r and H_{cj}.
- The desired properties and thermal stability can be optimized by a judicious mixture of Nd-Y-Dy.
- The YDy-based $R_2Fe_{14}B$ magnets are very promising for high temperature performance.

WT-096 Ames Alloy Composition Converted into 100 kg of Particulate (MQP-11HTP) by Magnequench International

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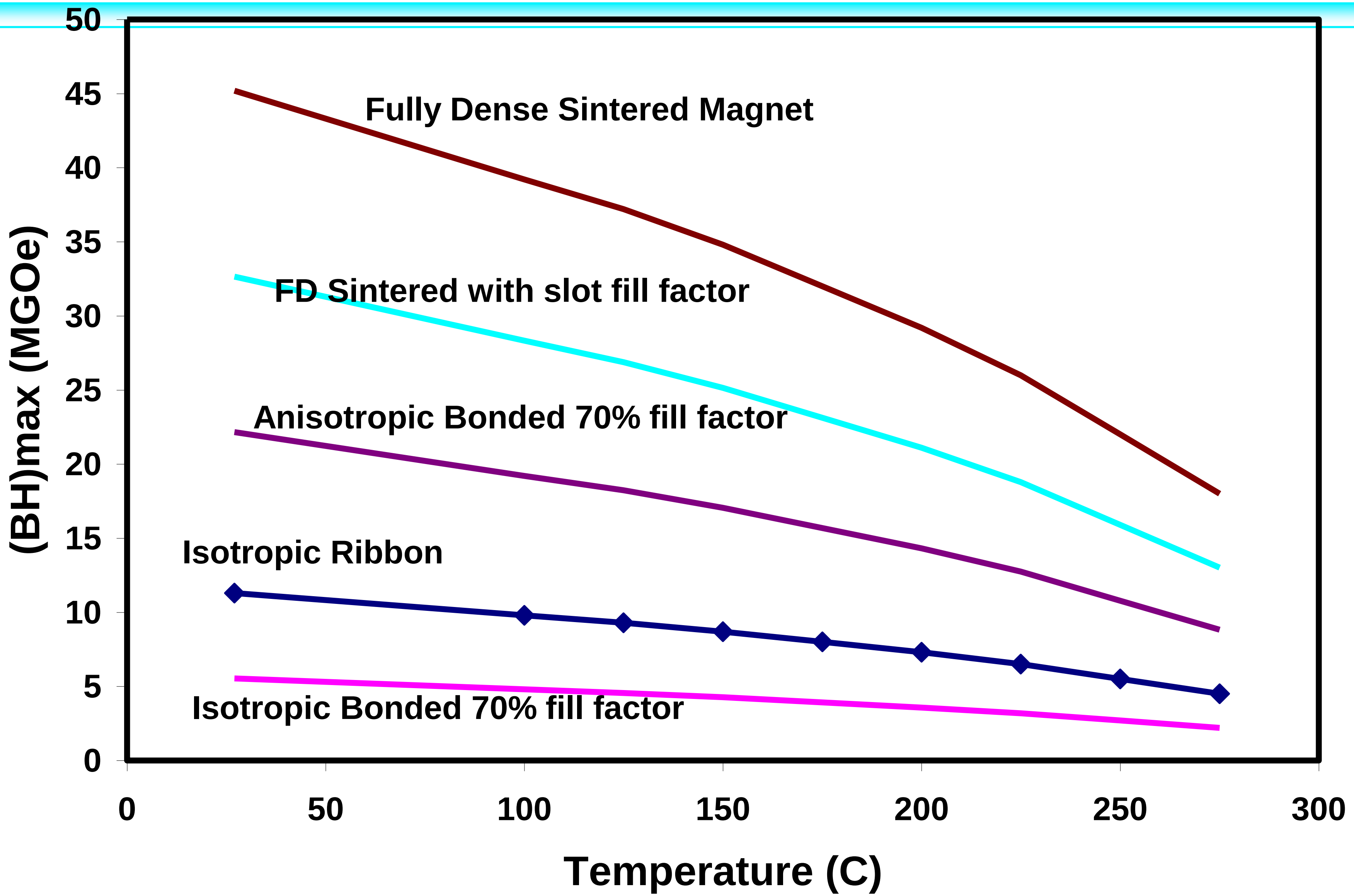
Estimated alloy performance



Estimated Magnet properties

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