Enabling the production of large HRE lean magnets with homogeneous microstructure –

The particle size effect in the 2-powder method and core-shell development in large magnets

Fraunhofer Research Institution for Materials Recycling and Resource Strategies
28th of July 2025 | REPM 2025 Tsukuba, Japan | Konrad Opelt

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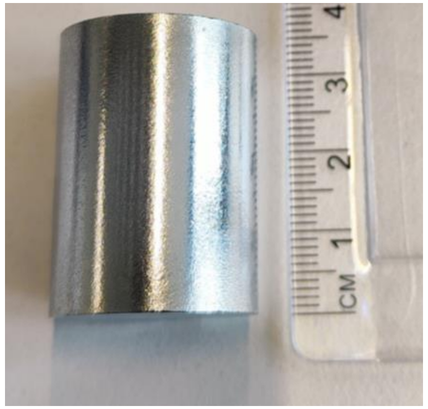

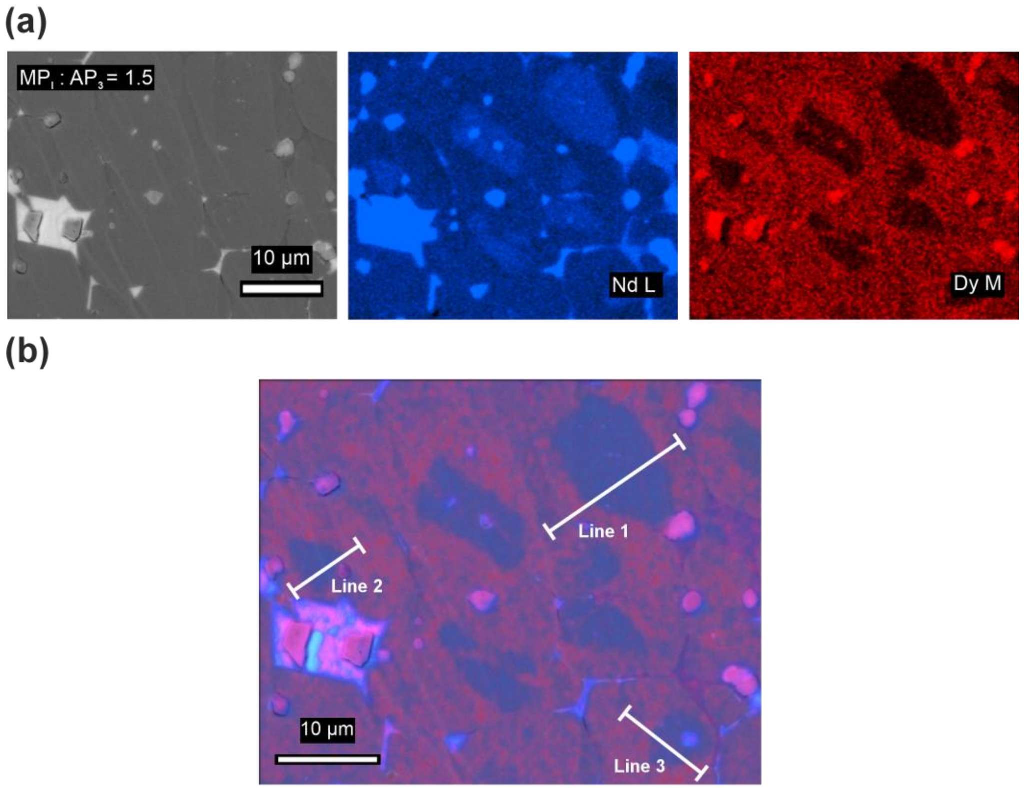

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Introduction

Fraunhofer-Gesellschaft worldwide

Fraunhofer Representative Office, Tokyo

Fraunhofer Innovation Platform for Fibers, Processing and Recycling Solutions at Innovative Composite Center, Kanazawa

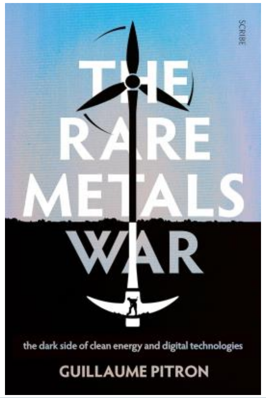
Overview

- Headquarters in Munich, Germany
- 76 Institutes and Research Facilities
- 32 000 employees
- Annual business volume 3.4 bn €

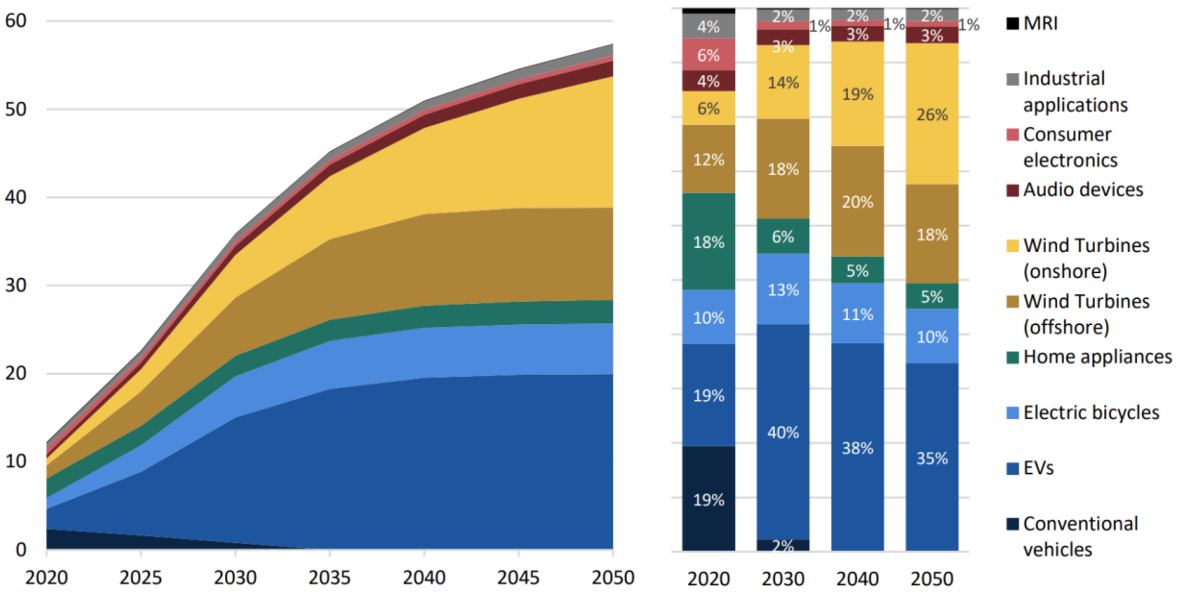
Introduction

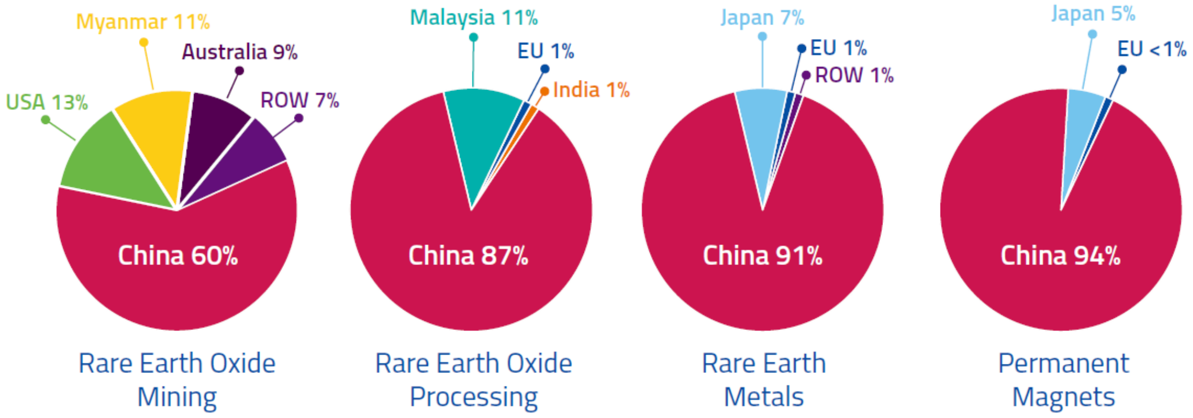
Criticality of NdFeB magnets

- The NdFeB market is driven by rising demand for **electromobility** and **wind power**
- Demand for NdFeB in the EU will increase from **10 kt to 55 kt** between 2020 and 2050
- Import volume 2023: approx. 700 million € (9,000 t) of NdFeB magnets, **Germany second largest importer** worldwide after Japan
- High need to **reduce dependency** especially of HREs on third countries
- Elemental cost (metal)
  - Neodymium: $ 75.95 per kg
  - Praseodymium: $ 82.89 per kg
  - Dysprosium: $ 298.70 per kg
  - Terbium: 1229.60 $ per kg



Demand for NdFeB magnets in the EU for selected applications in kt per year





R. Gauß, et al, Rare Earth Magnets and Motors: A European Call for Action. A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin, 2021.
CEPS, Developing a supply chain for recycled rare earth permanent magnets in the EU, 2022.
www.mineralprices.com

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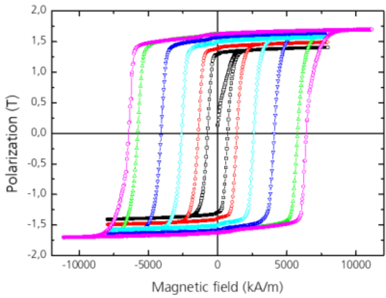
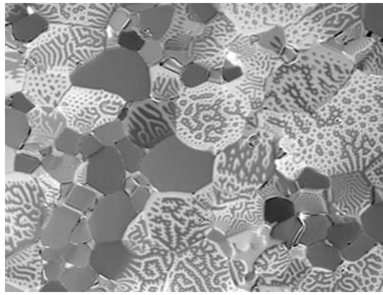
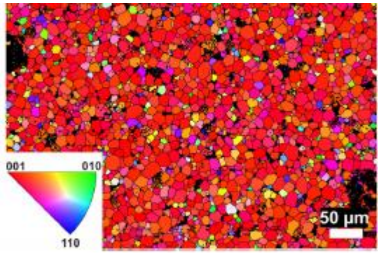
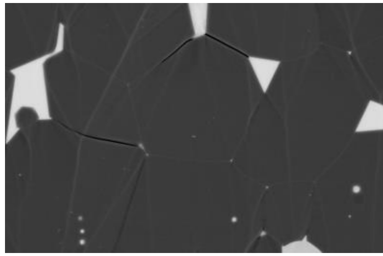
Pilot plant for magnet production and recycling @ IWKS

Synthesis and analytics









Research focus

Development of technologies for the magnet production and recycling in the batch size of 10 – 50 kg and technology transfer to industrial size manufacturing

→ Sintered magnets | rapid-quenching | additive manufacturing

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Introduction

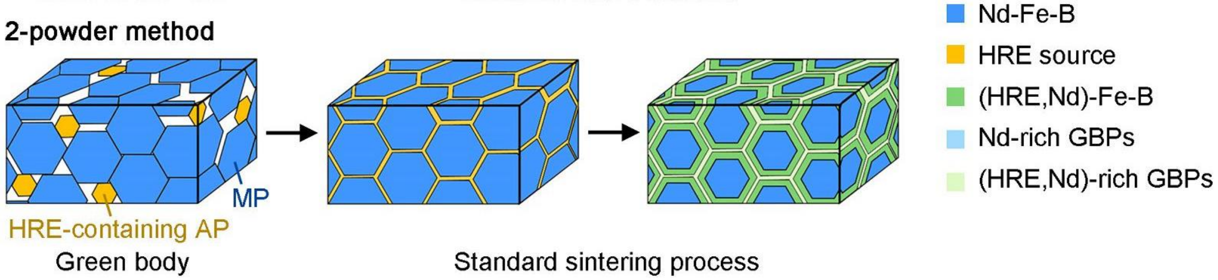
2-powder method

Process for grain boundary modification

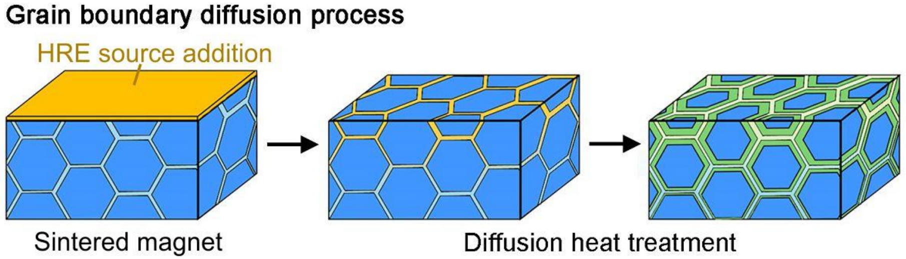
- Blending of two different $RE_2Fe_{14}B$ powders
- Heavy rare earth free main phase powder (MP) with ideally at least 50 % - 100 % higher average particle size
- Mixed with a HRE (such as Dy) containing anisotropy powder (AP)
- During the sintering process the smaller AP particles turn earlier into the liquid phase and surround the MP particles
- Formation a core-shell structure

- Advantage compared to GBDP
  - No additional HRE source
  - No additional coating step
  - No additional cost and time-intensive heat treatment
  - No limitation of magnet size

WO 2016/180912 AI, November 2016.
WO 2025/082920 October 2023.



K. Opelt et al., Acta Mat. **270** (2024) 119871

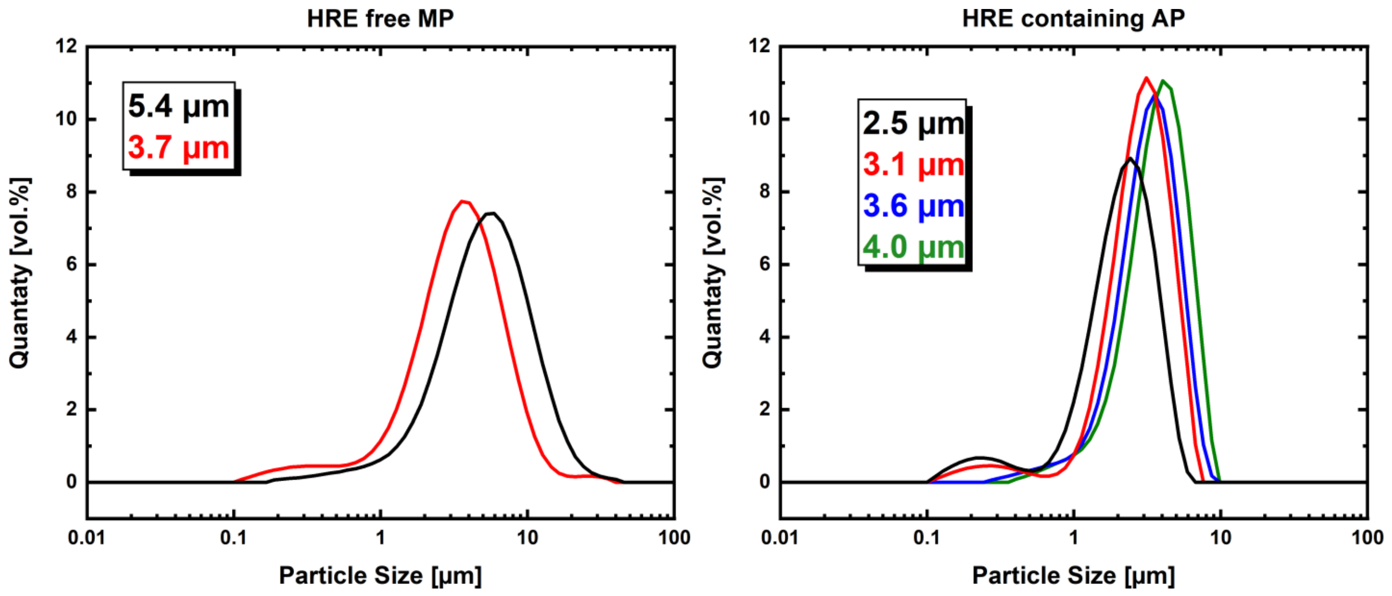


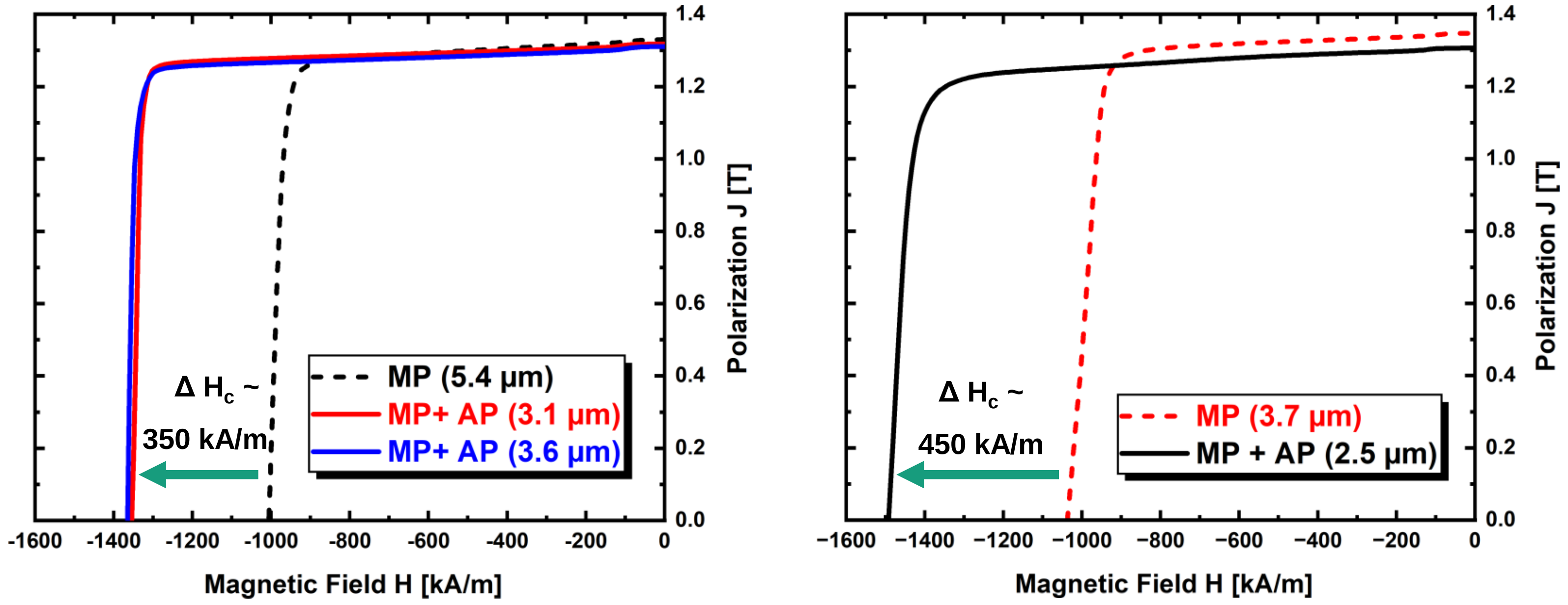
K. Opelt et al., Acta Mat. **270** (2024) 119871

The particle size effect

The particle size effect

- Two HRE free MP and four HRE containing AP
- All APs include 10 wt.% Dy
- Blending of MP and AP with a ratio of 80/20
- All powder mixtures include 2 wt.% Dy





- Coercivity gain between 350 kA/m and 450 kA/m

➢ **100 kA/m difference is related to the particle size effect, meaning that smaller grain sizes lead to higher coercivity**

  Manuscript under preparation

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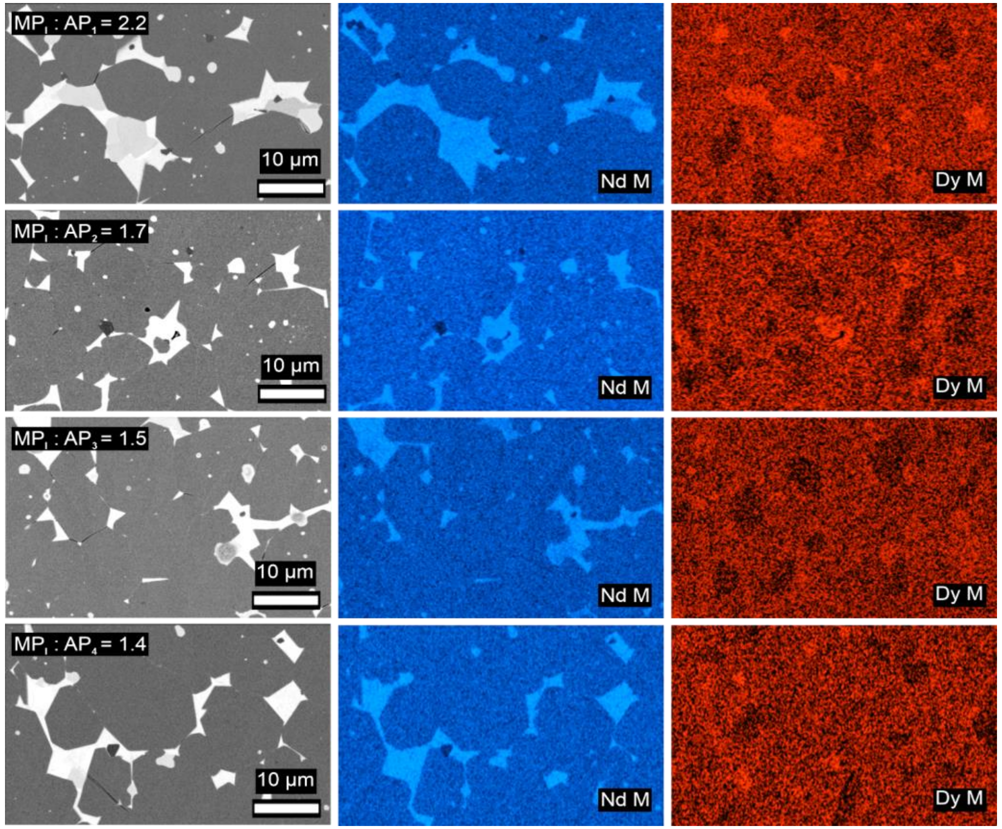
The particle size effect
SEM investigations

MP (5.4 µm) | **AP** | **MP (3.7 µm)**

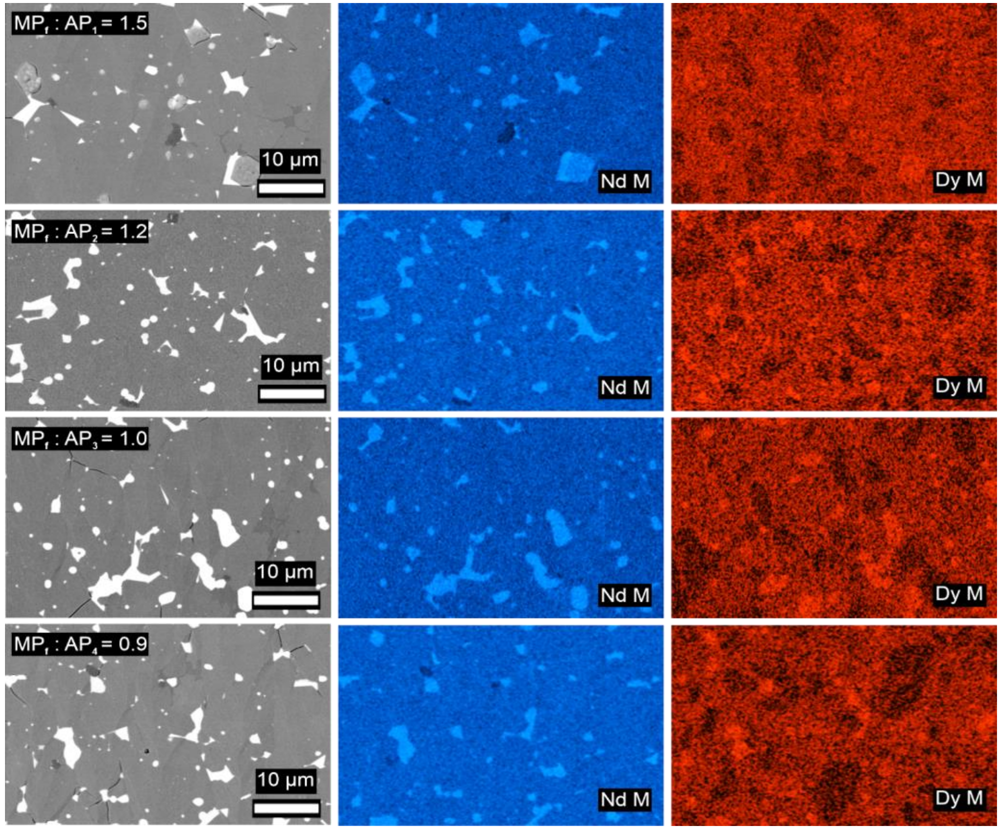


2.5 µm

3.1 µm

3.6 µm

4.0 µm



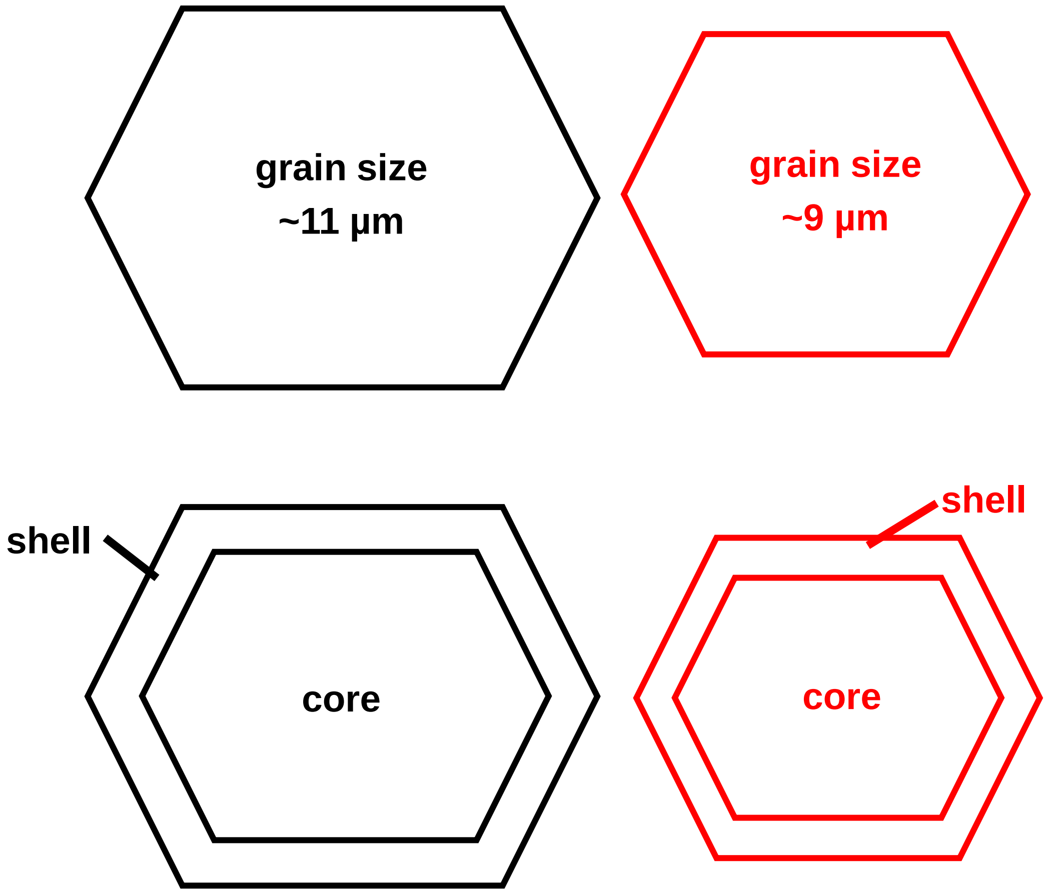
- Development of a core-shell structure for all magnets
- Even for similar particle sizes of MP and AP

The particle size effect

Core-shell development

- The average grain size after sintering for the mixtures with **MP (5.4 µm)** is larger compared to the **MP (3.7 µm)**
- The same trend is observed for the core thickness of the core-shell structure
- However, the shell thicknesses are in the similar range for all sintered magnets, independent of the initial powders
- The thickness of the shells (~ 2 µm) is assumed to be only related to the presence of the APs

➢ **The mechanism for the core-shell development is assumed to be the precipitation of the Dy atoms during the sintering procedure**



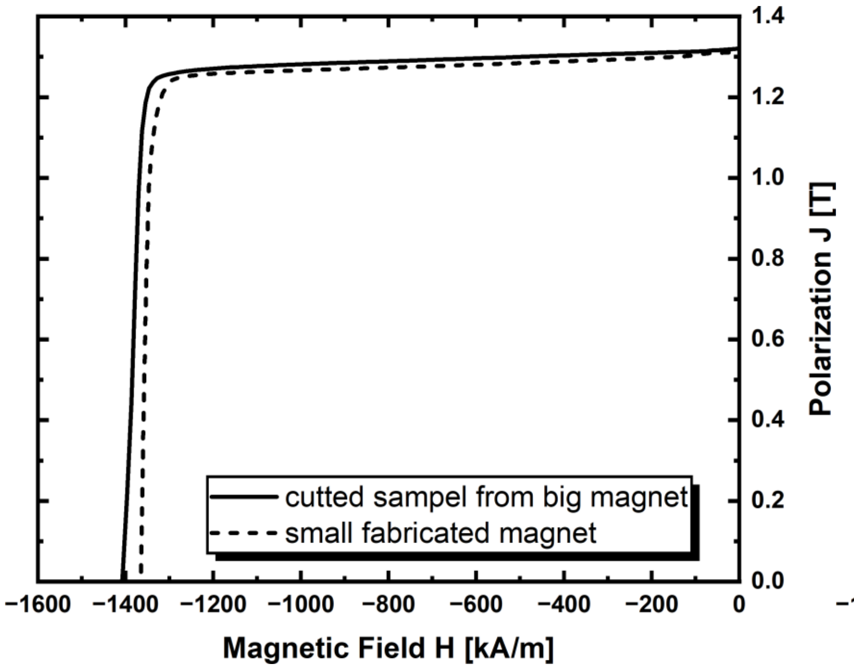
 1 September 2025 Manuscript under preparation

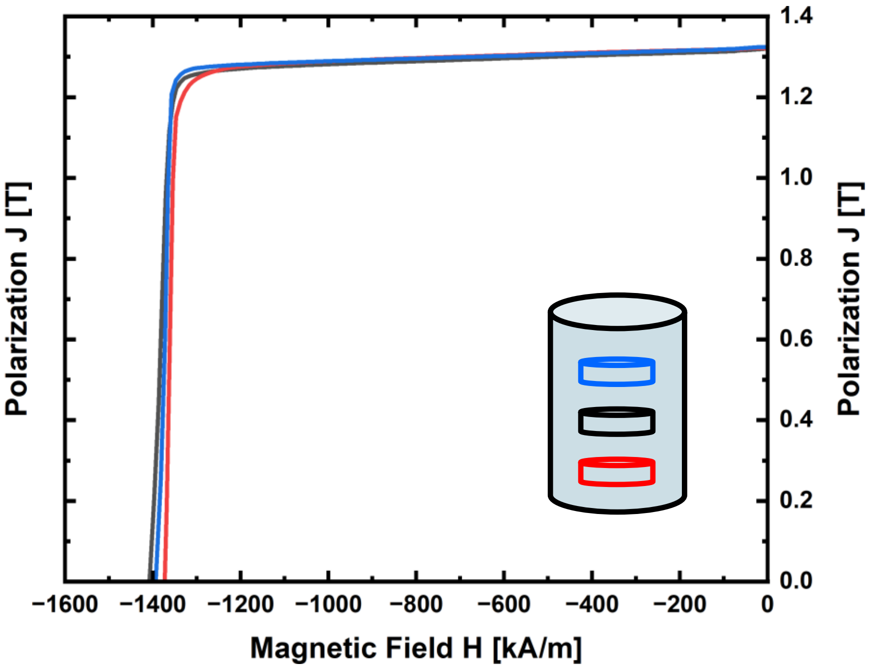
Manufacturing of large magnets via the 2-powder method

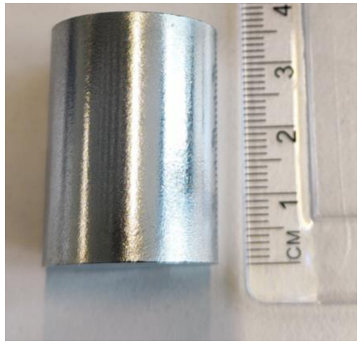
Manufacturing of large magnets via the 2-powder method

Magnetic properties

- 350g magnet with dimensions of approx. 45 mm in height and 40 mm in diameter
- Cut out smaller samples with 5 mm in height and 12 mm in diameter
- ➢ **Homogeneous magnetic properties throughout the whole big magnet**







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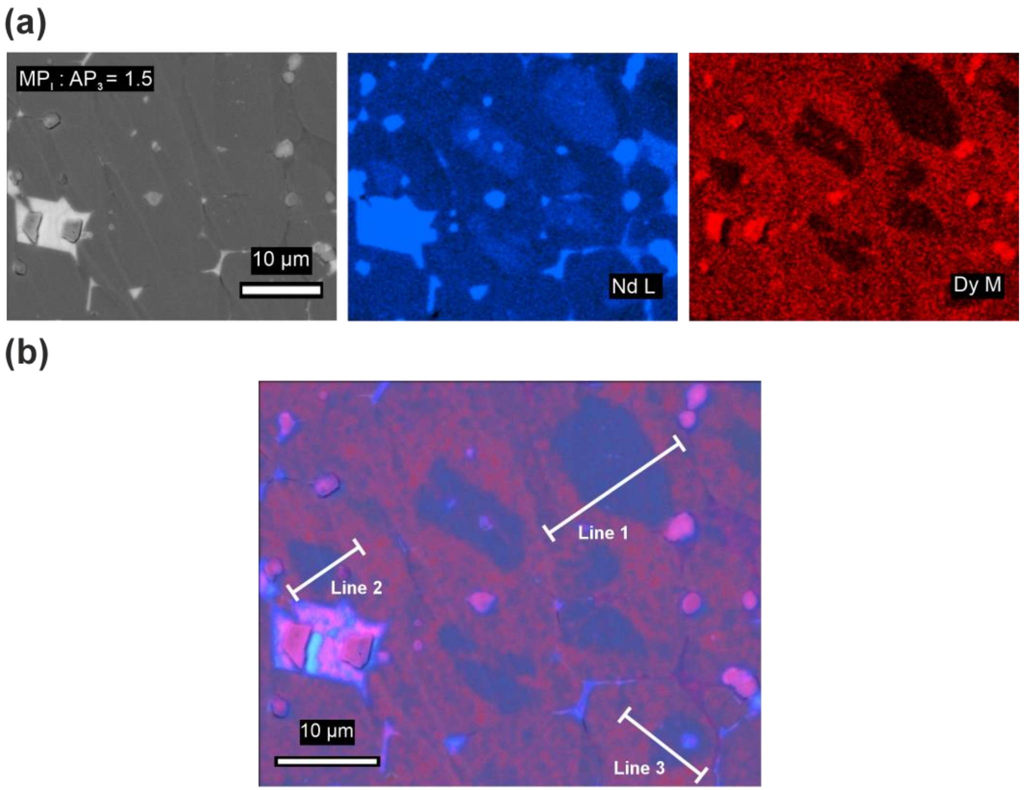
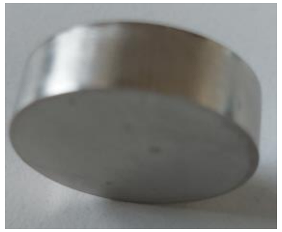
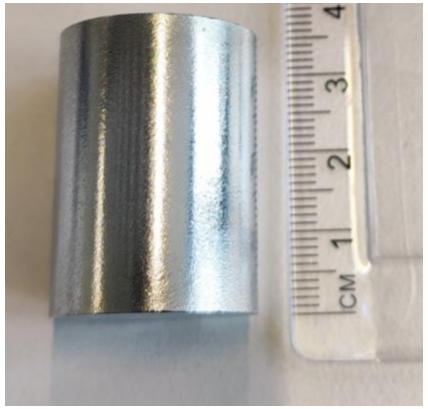
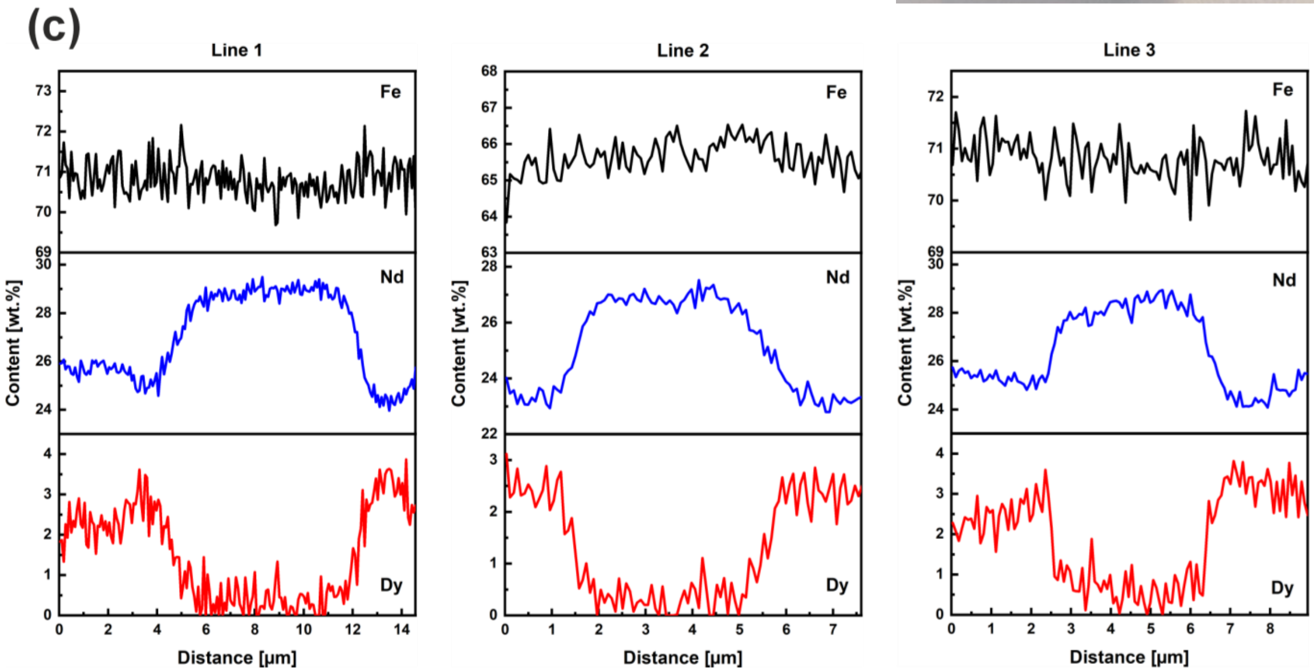
Manufacturing of large magnets via the 2-powder method

SEM investigation





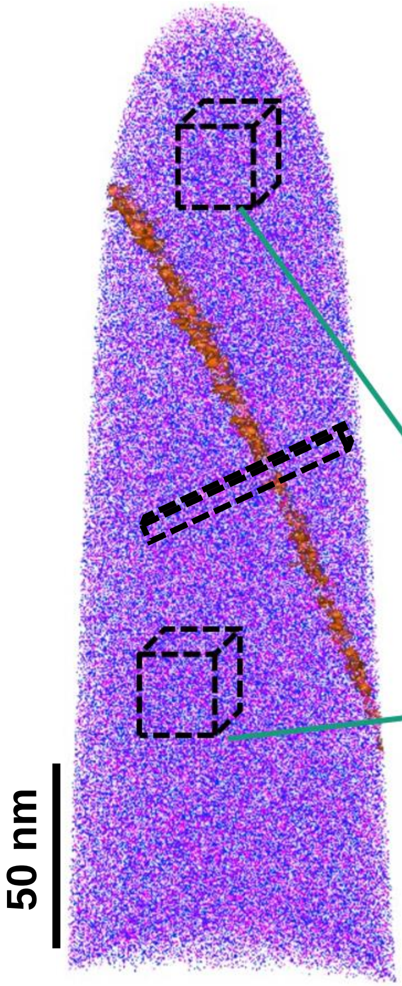


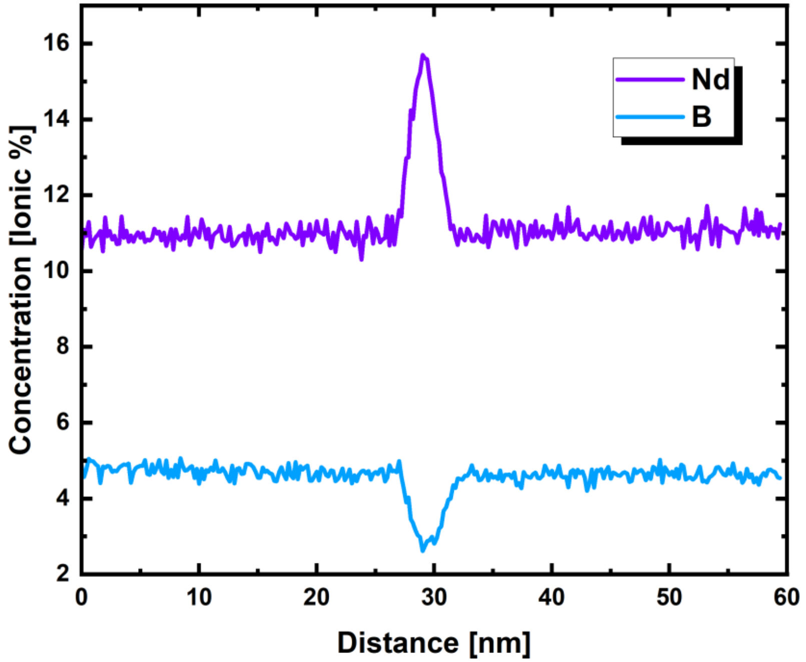


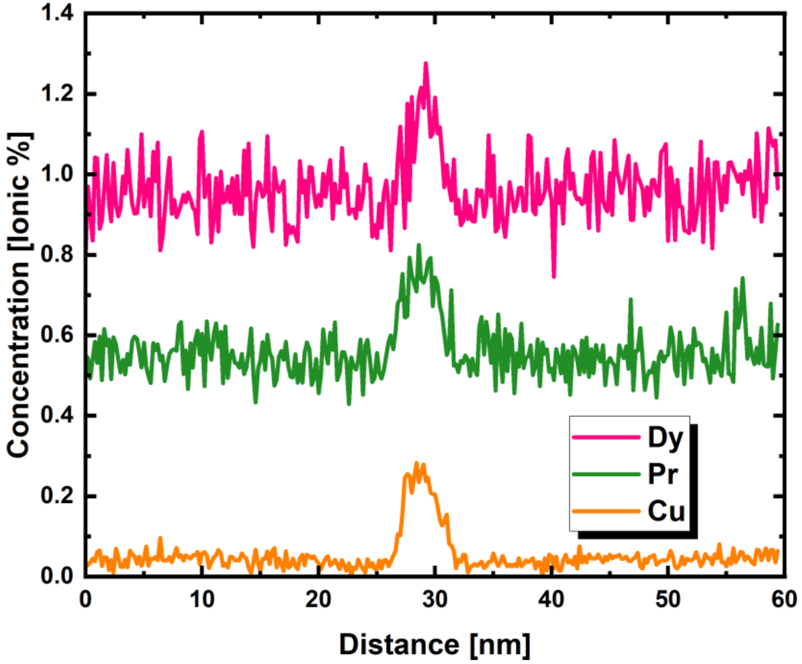
➢ **SEM shows the formation of a homogeneous core-shell structure in the whole volume of the 350g magnet**

Manufacturing of large magnets via the 2-powder method

Atom probe tomography







Element	at. %
Nd	10.93
Dy	0.94
Pr	0.55
B	5.05

- Nd, Dy, Pr, Cu, **increase at GB**
- Fe, B **decrease at GB**

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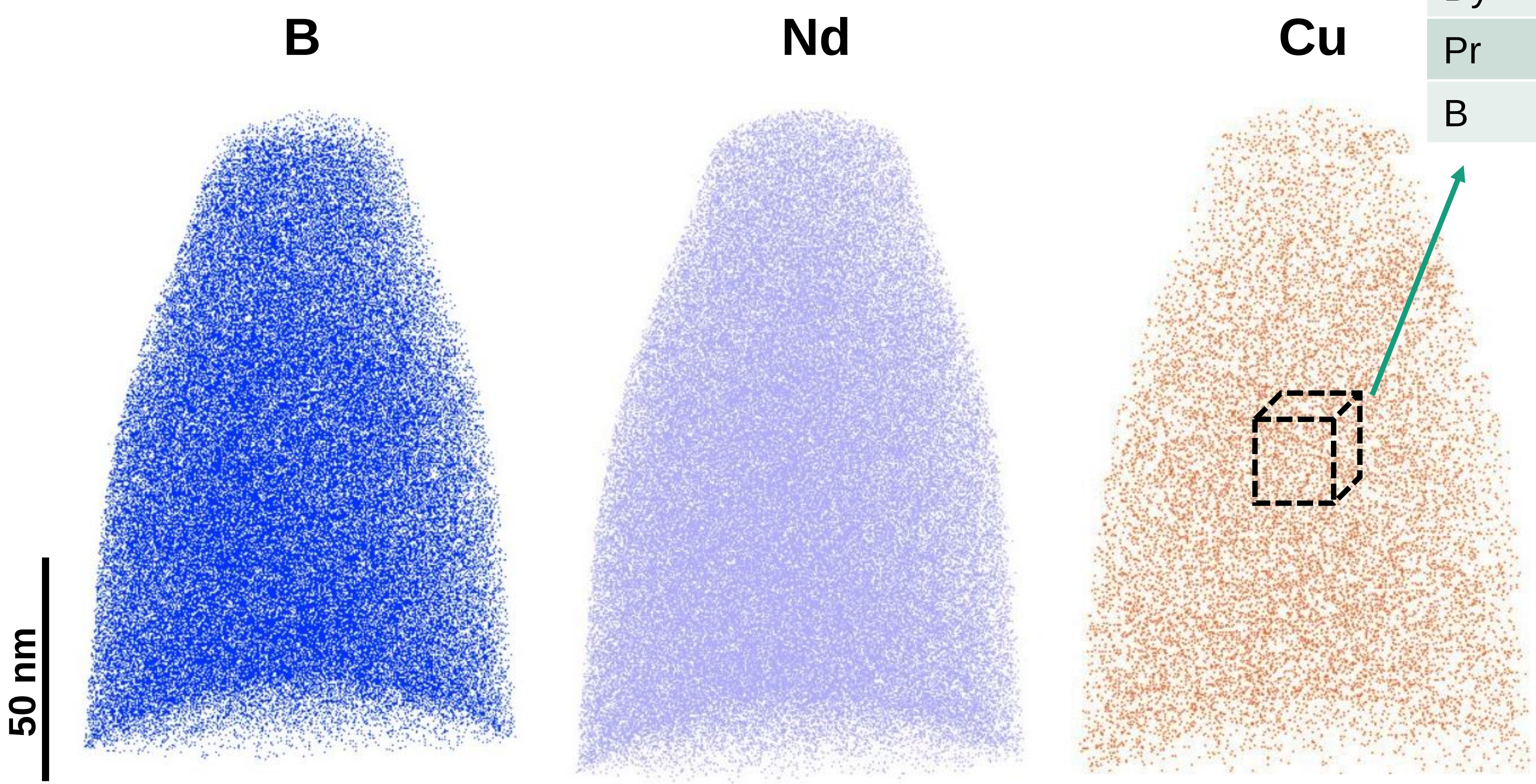
Manufacturing of large magnets via the 2-powder method

Atom probe tomography

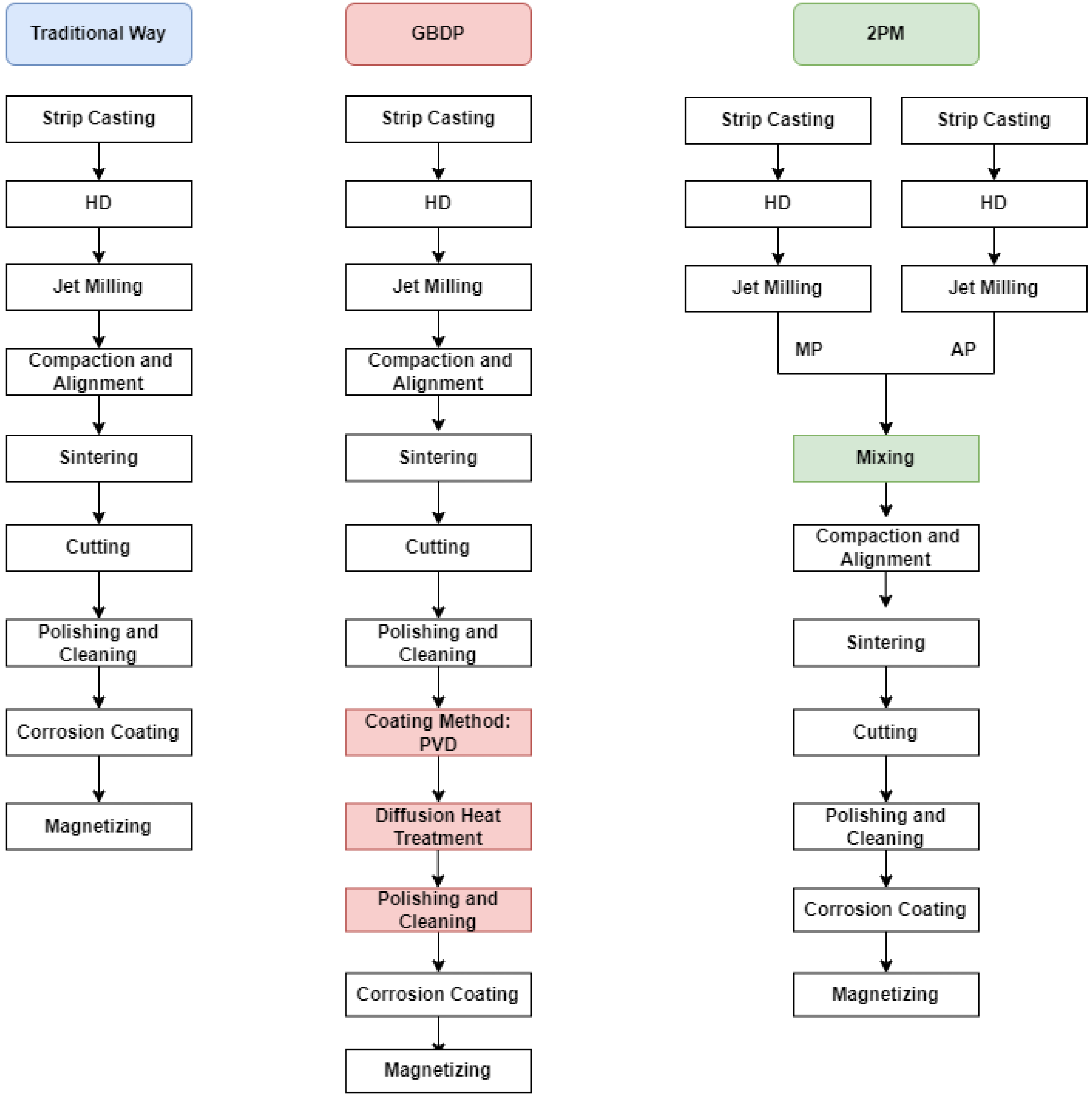


Element	at. %
Nd	12.16
Dy	0.1
Pr	0.13
B	4.64

- **Higher Nd content and lower Dy content in the core site**

Life-Cycle-Assessment

Life-Cycle-Assessment



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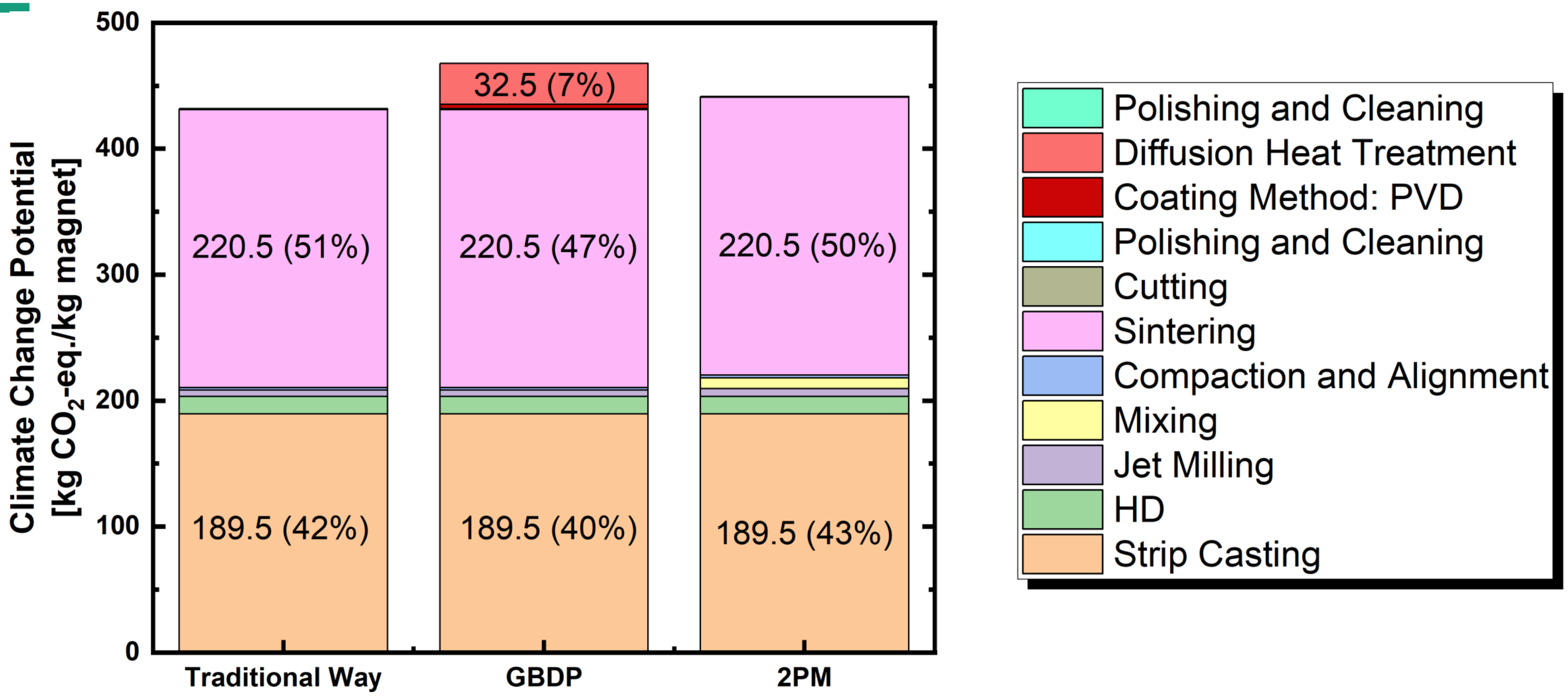
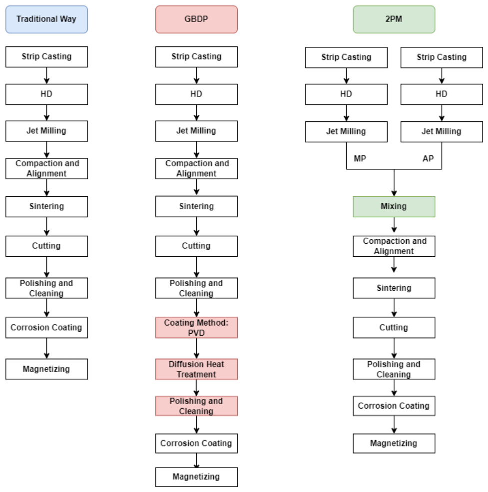
https://www.horiba.com/esp/applications/energy-and-environment/energy-usage-optimization/lca/

Life-Cycle-Assessment





- Industrial production shows about 10 times less climate change potential compared to our technical scale processes
- Therefore the values shown here has to be compared relatively
- Roughly 8 percent higher CO_2-eq./kg more consumption for the additional GBDP steps (only valid for thin magnets)
- ➢ **LCA demonstrates the energy-saving potential of the 2-powder method**

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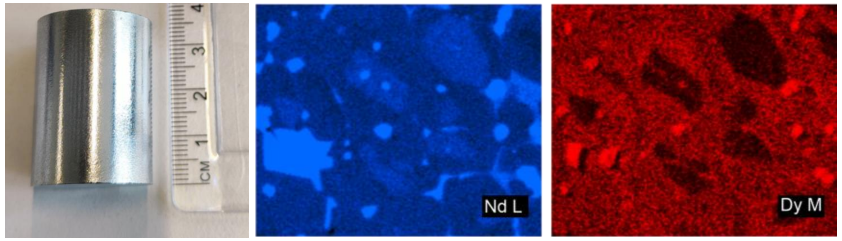
Summary & Outlook

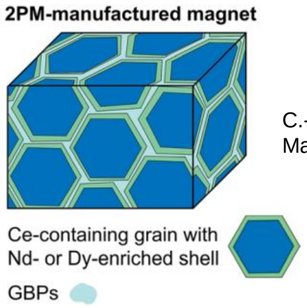
Summary & Outlook

- The investigation of different particle sizes for MP and AP shows a coercivity gain up to 450 kA/m with 2 wt.% Dy, whereby the shell thickness is the same for all magnets
  - ➢ Core-shell development is assumed to be the precipitation of the HREs from the AP



- 350g huge magnets with a **homogeneous core-shell** structure through the **whole volume** were produced, which is not possible with the GBDP

- This shows a large potential also for the utilization of the rare earth balance
  - ➢ Increasing the Ce content by engineering a high Ce-containing grain and performing the magnetic hardening with a Nd rich shell



C.-C Lin et al., Adv. Eng. Mater. 2025, 2500054

- LCA shows the CO_2-eq. saving potential of the 2PM compared with the GBDP

- Next step is to adjust the HRE content in the AP to further improve the coercivity gain by using the 2PM

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Thank you very much for your attention

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Bundesministerium für Bildung und Forschung

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