Plasma separation for rare earth elements recycling

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Differential particle confinement effects in plasmas can in principle arise from many different physical phenomena. Conceptually, one can exploit these differential effects to discriminate elements based on a given physical property. Examples of such processes include atomic-mass based separation relying on centrifugal effects [1], differences in gyro-radius [2] or collisionality gradient [3] and laser separation taking advantage of differences in excitation energy [4]. However, since plasma separation techniques were initially primarily contemplated with the goal of separating isotopes [5], most of the foundational work on this research topic has focused on separating elements with small differences in atomic mass. In addition, owing to the fact that throughput decreases exponentially with mass difference in plasma centrifuges - one of the leading concept at the time [6] -, the potential of plasma separation for high-throughput applications remained largely unexplored.

Yet, this pattern has changed in the last decade, which has seen a renewed interest in plasma differential effects for the purpose of separating elements with large mass differences (typically tens of atomic mass or more) [7, 8]. This new research effort has been motivated, at least in part, by the realization that high throughput plasma separation based on atomic mass holds significant upside potential for nuclear waste cleanup [9] and spent nuclear fuel (SNF) reprocessing [10, 11, 12]. Indeed, by relaxing the constraint on mass difference, it then becomes in principle possible to access much higher throughput, which in turn makes plasma separation conceptually attractive for a variety of new applications. Another strong driver for the development of plasma separation techniques is that, besides the ability to separate elements with similar chemical properties, they are anticipated to have a much smaller environmental footprint than competing chemical separation techniques.

Recently, we assessed the potential of plasma mass separation techniques for rare earth elements (REEs) recycling from neodymium - iron - boron (NdFeB) magnets [13] (see Fig. 1), and showed that a generic mass filter model representing an ideal rotating plasma mass filter offers comparable performances to competing techniques currently under development, but with much lower environmental impact. Furthermore, preliminary cost estimates suggest plasma separation could be cost effective for this application given REEs high cost and the versatility of

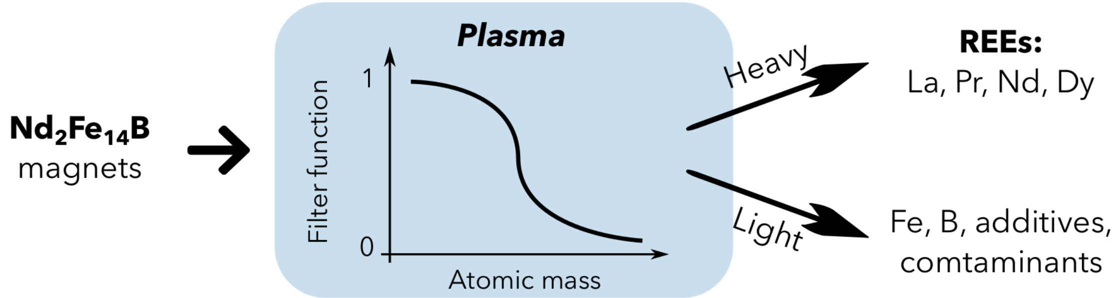

Figure 1: Plasma mass filtering for neodymium - iron - boron magnets recycling [13]. Elements are separated in two groups based on atomic mass, separating out REEs from non-REEs.

REEs supply chain.

The mass gap between species to be separated for REEs recycling is about 40 amu. Indeed, although advanced plasma schemes could in principle separate one REE from another [13], we focus here on the recovery of mixed-REEs from non-REEs in a single stream, as shown in Fig. 1. As illustrated in Fig. 2, this mass gap is comparable to actinides-lanthanides separation in SNF reprocessing, and about 1.5 times larger than for nuclear waste cleanup. This suggests that large throughput processing is possible. On the other hand, REEs recycling stands out from the two other applications in that the mass fraction of elements to be separated out can be as large as 30%, while it is about 10% for SNF reprocessing [11] and as low as 3% for nuclear waste cleanup [9]. One of the benefits of this feature is that, since the minimum cost of plasma processing typically scales with the number of atoms in the input feed, the "cost efficiency of" plasma separation is greater. Note though that this is not rigorously true since the minimum cost actually depends on the stoichiometry weighted sum of the ionization energy of each element. On the other hand, this relatively large mass fraction in the input stream invalidates an assumption which generally holds true for other applications, namely that the elements to be separated out are trace elements. As a result, it is expected that, in the absence of a background processing gas, the plasma formation and plasma properties will be affected by both REEs and non-REEs present in the input stream.

Future work should elicit additional, and possibly dominant, drivers to choose a particular plasma mass filtering concept for NdFeB magnets recycling. Examples of key drivers include the energy cost per separated REEs atom, the purification (separation factor) offered by a given concept for the particular task of NdFeB magnets recycling, and also technological considerations. Nevertheless, the fact that the elements to be recovered (REEs) can make for a non negligible fraction of the input stream already provides insights into this choice. Indeed, the

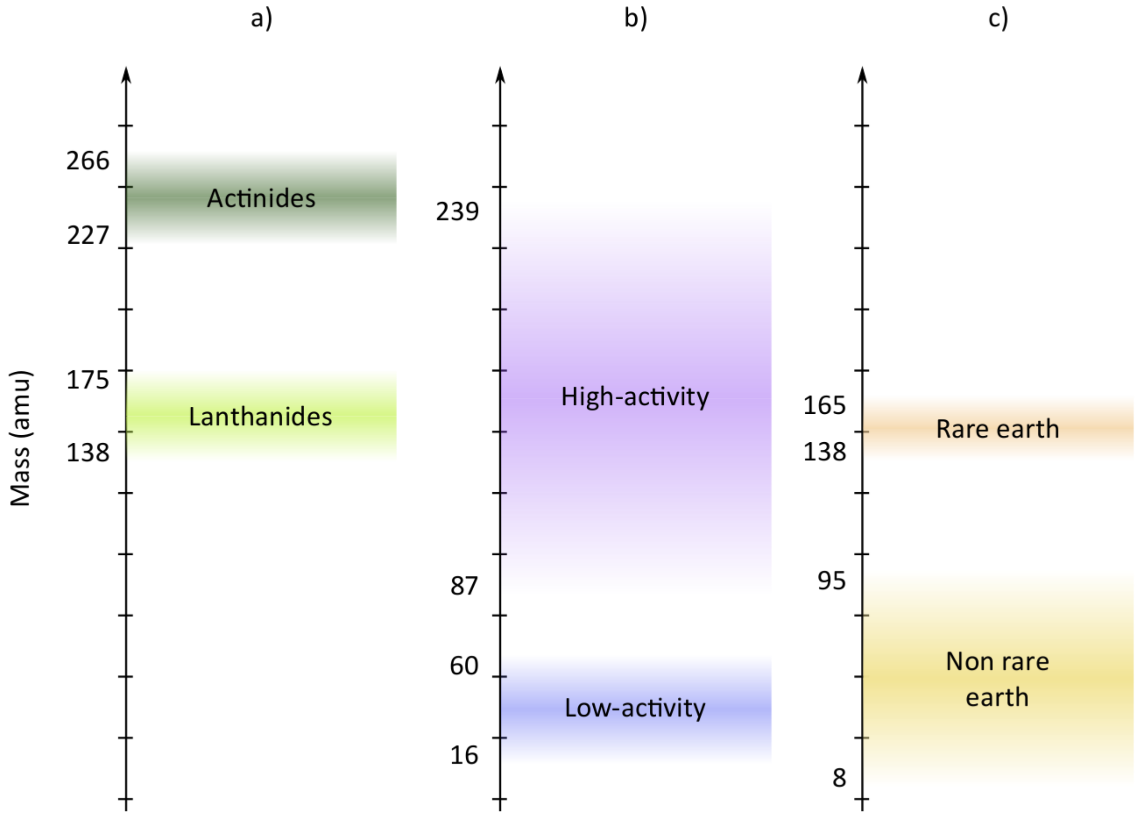

Figure 2: Typical atomic composition of the input feed for three applications of high-throughput plasma processing: (a) SNF reprocessing [11], (b) nuclear waste cleanup [9] and (c) NdFeB magnets recycling [13].

various plasma mass separation concepts proposed to date rely on a variety of physical mechanism (see, *e. g.*, Refs. [7, 8] and references therein), and each mechanism is most efficient for a specific set of operating conditions within a large parameters space, including composition.

In some plasma mass filter concepts, the differential confinement properties at play depend directly on atomic mass. This is for example the case of gyro-radius based separation [14, 2] or separation in curved magnetic fields [15]. Neglecting other phenomena, separation in these filter concepts does not depend on the mass breakdown in the input feed, and only the atomic mass distribution is required to dimension these devices.

This is in contrast with other concepts, such as plasma centrifuges [6] and the Magnetic Centrifugal Mass Filter (MCMF) [16], in which mass separation arises through the mass dependence of collisional frequencies. Since collision frequencies also depend on the relative densities, proper design of these devices requires knowing *a priori* both the mass distribution of the elements and their relative density. This becomes particularly relevant when elements to be separated out are not trace amounts.

Based on this simple consideration, it would seem that designs in which differential effects do not depend on plasma composition are preferable for REEs recycling. However, it is important to note that the picture drawn here is over simplified. Practically, there is not only two groups here, but rather a continuum of possible separation concepts ranging from mostly unaffected to strongly affected by plasma composition. For instance, even if separation does not occur as a result of collisionality in some mass filter concepts (say *e. g.* gyro-radius based filters), collisions will still affect separation, so that performances will in turn depend on relative densities. Another example is the double well mass filter [17] where performances will depend on collisionality and therefore on composition, but where mass separation will occur no matter the composition. Finally, robustness with respect to composition is only one of the numerous metrics one can use to assess the performances of plasma mass filters for a specific application. For example, it may be that the same designs which show little dependence on composition are less capable of operating at high plasma density, which is critical for the high-throughput operation. Consequently, the choice of a particular concept will ultimately be a trade-off between the many different metrics and their associated limitations.

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