A FRAMEWORK FOR ENVIRONMENTALLY CONSCIOUS DESIGN OF PARTICLE ACCELERATORS

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Abstract

Particle accelerators typically use multiple times more electrical energy than the kinetic energy of the accelerated particles, resulting in low plug to beam efficiencies. The resources required for such machines are also substantial. Considering these points, we present a multifaceted approach with which we can calculate both the carbon emission impact for production and operation of particle accelerators, as well as the relative scarcities of materials used and their possible radioactivation during a lifecycle. To demonstrate a comprehensive use case, we apply these methods to the EcoCyclone permanent magnet cyclotron concept and compare to a normal-conducting coil powered cyclotron with the same output particle energy: the IBA Cyclone®Kiube. We find the two machines produce similar lifetime carbon emissions where the electricity supply is more carbonised, but caveats such as differing impacts of different material sourcing apply. We discuss how the calculated impacts may change over time, noting increasing electricity cost with decarbonisation, and argue these analyses should be performed during the design phase of all new accelerators.

INTRODUCTION

Particle accelerators typically use many different components often containing scarce materials in their construction, from copper in normal-conducting radiofrequency cavities to rare-earth metals in permanent magnets and HTS conductors. In addition to this, the electrical wall-plug efficiency of particle accelerators is regularly poor due to both RF plug-to-beam efficiency and magnets required for beam manipulation [1].

As different electricity grids have different contributions of high/low/zero-carbon energy sources, and so any electricity saved is beneficial, energy efficiency is a good first indicator of environmentally conscious design.

Cyclotrons typically consume between 10 and 100 kW of electrical power solely for the main coils [2], providing the main magnetic dipole field. While reducing the electricity consumption (and related carbon emissions) of a cyclotron by this amount would be a substantial prize, we must consider the cost in terms of the scarcity of materials required with the carbon emissions for production (and the increased financial cost).

In the work presented here, we develop a method to evaluate and compare the full carbon impact of production and use of particle accelerator components and the scarcity of materials used, applying these as an example to two cyclotron magnet designs from IBA: the Cyclone(R) Kiube [3] and the EcoCyclone concept [4]. We then discuss material sourcing, machine manufacture and use in different countries, and how this affects the overall impact of the machine.

We then briefly discuss water usage and conclude that the framework presented here is suitable for any accelerator component. For the example of magnets presented here, we conclude some rare minerals/materials used in pursuit of lower operation emissions cause high production emissions. In some cases, we find this completely counterbalances what these changes would otherwise save over the lifetime of a device, though this is found to depend on the country of manufacture and country of installation.

STUDY CASES

To best illustrate the framework, we present its application to two designs of cyclotron magnet, with the same methods applicable to any device in a particle accelerator. The properties of each design are given in Table 1.

Table 1: Magnet Properties

Magnet:	**Kiube**	**EcoCyclone**	
		NdFeB	SmCo
Steel Mass[t]	14	35	39
Copper Mass[t]	2	0	0
NdFeB Mass[t]	0	8.4	0
SmCo Mass[t]	0	0	12
Total Power[kW]	19	0	0

The IBA Cyclone(R) Kiube represents a compact cyclotron already on the market, consisting of a square yoke and normal-conducting copper coil. The "total power" we consider for this case is the sum of the coil and the coil-cooling system (water pump and heat exchangers) of 19 kW.

The IBA EcoCyclone represents a possible solution to implementing permanent-magnet cyclotron magnets, providing a field equivalent to that of the Kiube. Two options exist for this design: neodymium (NdFeB) or samarium-cobalt (SmCo) permanent magnets, with the latter requiring more steel to compensate for the typically weaker magnetic strength at room temperature [5]. We shall examine both options for the study here.

We consider a 25-year magnet lifetime, with possible extension to 30 years, with an average of 8 hours per day magnet up-time.

CARBON EMISSIONS

To obtain the carbon emissions from production and electricity consumption during use, we use the Ecoinvent Database [6, 7]. Particularly, carbon emissions values in

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kg-per-tonne for the magnet steel (fairly uniform worldwide, as eco-friendly production of steel is still limited), for the coil copper, and for permanent magnet materials (at time of writing largely limited to production in China [8]) as a possible replacement for the electromagnet/copper.

For the example of the Kiube, the steel mass is approximately 14 t and main coil copper mass 2 t. From these, we can calculate combined production emissions of 89 t of CO_2.

In the case of the EcoCyclone using NdFeB magnets, the steel mass is 35 t (more steel being required to focus flux from the permanent magnets) and the NdFeB magnet mass is 8.4 t, resulting in production emissions of 520 t of CO_2. For the EcoCyclone magnet, there is no electricity use, and therefore there are no emissions during operation.

In the case of the EcoCyclone using SmCo magnets, the steel mass is higher at 39 t, and the SmCo magnet mass is 12 t, with resulting production emissions of 510 t of CO_2 due to the smaller carbon footprint of SmCo.

For the Kiube, we use a total power associated with magnet operation of 19 kW. The carbon emissions associated with this electrical power consumption depend on the source of that electricity, therefore this depends on the installation location of the magnet.

We use three examples of electricity carbon emissions from the database (in kg CO_2 per kWh): a high carbon electricity grid where coal power is typical ($0.94\,\mathrm{kg\,kWh^{-1}}$), a medium carbon electricity grid where natural gas and coal are typical ($0.46\,\mathrm{kg\,kWh^{-1}}$), and a very low carbon electricity grid where nuclear and hydroelectric are typical ($0.07\,\mathrm{kg\,kWh^{-1}}$). With these, we can plot the carbon emissions over the lifetimes of the two examples (shown in Fig. 1).

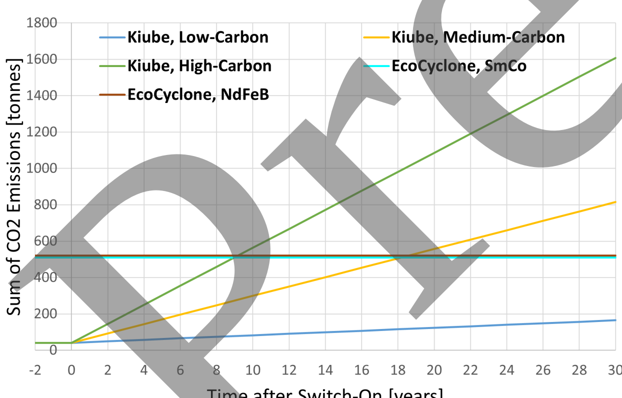

Figure 1: Total carbon emissions of the EcoCyclone magnet (powered using permanent magnets), and Kiube based in electricity grids of differing carbon intensity. We note the EcoCyclone is most beneficial where electricity is carbon-intensive.

We see that, in this case, the lifetime carbon impact of swapping copper coils for permanent magnets depends heavily on the electricity grid the machine will be attached to. In the high carbon grid case, the Kiube magnet will have higher lifetime carbon emissions than the EcoCyclone magnet after 9 years of operation, with the medium carbon grid increasing this to 19 years. For operation on a low carbon electricity grid, there is no tradeoff within an estimated 30-year machine lifetime.

We have two points to note; firstly that cyclotron magnets may be reusable, which can further increase the carbon impact of the Kiube as compared to the EcoCyclone (as an extension to the right of Fig. 1). The second point we note is the carbon emissions from production depend on the methods of mining and refinement of the materials, and could be considered subject to change with time and location.

SCARCITY

For long-term sustainability, we must also consider the scarcity of materials we use as they may be of high demand elsewhere. To quantify scarcity, we use an equivalent mass of antimony (Sb, a rare earth metal), the values for which were also obtained from the Ecoinvent Database.

In the case of the Kiube magnet, we find the steel yoke has the equivalent scarcity of just 0.024 kg Sb, while the coil copper has a scarcity equivalent to 17 kg Sb. The scarcity of the electricity used during a 30-year lifetime (again assuming an average of 8 hours per day) is equivalent to 0.27 kg Sb.

For the EcoCyclone NdFeB magnet, the yoke has an equivalent scarcity of 0.063 kg Sb, and the neodymium permanent magnet has an equivalent scarcity of 21 kg Sb. However, the SmCo permanent magnet in the alternative EcoCyclone design was found to have an equivalent scarcity of 114 kg Sb.

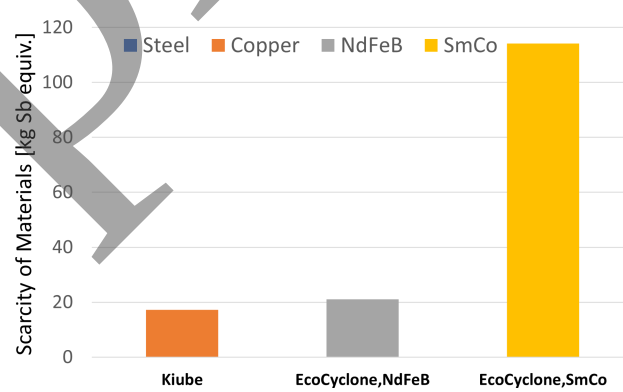

Figure 2: Total scarcities of the materials used in the Kiube magnet, and of those used in the EcoCyclone magnet using neodymium or samarium-cobalt magnets. We note the dominating materials here are the copper and permanent magnet materials, with the contributions from steel and electricity negligible by comparison.

The results are shown in Fig. 2, and show a clear preference for neodymium magnet over samarium-cobalt, in terms of scarcity. The scarcity of copper is rarely considered, but as shown in the results here should not be ignored.

ACTIVATION AND REUSE

To determine the potential for reuse of a particle accelerator component, possible activation of its constituents must be considered. For the design of the EcoCyclone, this has been considered for the case of the permanent magnet pieces in [4].

In that study, we considered two 18F radiopharmaceutical production targets, each with 150 µA incident beam current. This was simulated in MCNP6.3 [9, 10], with FISTPACT-2 [11] used to estimate the activation. The absorbed doses found of 2.1 mGy/hour for NdFeB and 3.9 mGy/hour for SmCo result in a required cool-down time (to be classified as non-activated or exempt by the IAEA) of 12 years for the NdFeB magnets and 100 years for SmCo.

We performed a study on the Kiube magnet coils using the same method, which suggested a cool-down time of approximately 50 years due to closer proximity of the copper to the vacuum chamber walls than the permanent magnets and the generation of ^{60}Co. This is a problem to consider when designing magnets; the greater magnetic efficiency of having the coils around the poles versus the reduced activation of having them farther away from the beam/vacuum chamber.

These results suggest that SmCo magnets are not reusable in this case. For such a scarce material reusability is vital, and we thus exclude the use of SmCo magnets. However, for NdFeB magnets (and arguably copper coils) the cool-down time is short enough to be stored and re-installed in another machine (possibly after a re-magnetisation in the case of NdFeB), or recycled. This means the carbon emissions from production could indeed be considered as spanning another machine lifetime (25-30 years), strengthening the argument for replacing a normal-conducting magnet.

CONCLUSION

To accurately evaluate the scarcity and carbon impacts of a particle accelerator component, we ideally need a long-term plan of lifetime, refurbishment, re-use, decommissioning and recycling. In many cases, the lifetime is not well known as while normal-conducting magnets can last 50 or more years [12], they may not find re-use following the project for which they were produced.

In the comparison made here (between the Kiube and EcoCyclone cyclotron magnets), we must consider that the carbon impact of the electricity which powers the coil is dependent on country of installation, and how this carbon impact might change over the magnet lifetime due to decarbonisation of the electricity grid. We should also bear in mind that production emissions depend on the production location.

We can also consider other environmental impacts; while potable water itself has a scarcity, water usage remains difficult to classify due to the many ways it can be used (large volumes stored, or released after being polluted, or released as vapour which itself is a greenhouse gas). These will also change substantially depending on regulations/location.

For further study, we could consider the scarcity of electricity to be dependent on the power drawn. Also of further interest would be particulate emissions during production (particularly the most carcinogenic PM2.5 [13]).

Ultimately, the choices made are not only determined by environmental impact, but also by cost. However, by researching design options of all new particle accelerator components with the framework detailed here, we can improve the position of the environmentally-conscious decision maker.

ACKNOWLEDGEMENTS

We would like to acknowledge the IBA Technologies division for their feedback, input and support for this research.

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