Using permanent magnets to reduce the impact of accelerators

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Reducing the impact of accelerator magnets

Particle accelerators are large, energy-hungry facilities. A large proportion of that energy is required to accelerate beams to high energies, typically using radio-frequency (RF) cavities. Another significant chunk of energy is taken up by the systems that steer and focus the beam. A beam of high-energy charged particles can be deflected using strong magnetic fields, which are usually generated by electromagnets spaced at regular intervals along the beamline. Dipole magnets produce a flat magnetic field suitable for steering a beam around the arc of a curve, whilst quadrupole magnets provide a focusing field analogous to the concave and convex lenses used in optical systems. The physics of particle beams means that quadrupole magnets must be installed at regular intervals along the beamline, otherwise the beam will quickly diverge and be lost in the chamber walls.

Particle colliders such as the LHC use superconducting magnets to generate the fields required to bend and focus their high-energy beams; the LHC, operating at a maximum energy of 14 TeV, requires fields of 8.3 T to steer beams round its 27 km circumference. These field levels are only feasible using superconducting magnets, cooled to 4 K. Synchrotron light sources, such as Diamond, SPring-8, and the ESRF, are more modestly sized, and only require fields in the 1-2 T range to steer beams around their main rings. Fields of this magnitude are usually achieved using resistive (non-superconducting) magnets, which utilise copper coils wound around high-permeability magnetic steel poles. In these 'iron-dominated' magnets, the poles determine the field shape, and must be precisely machined and aligned to produce the maximum possible field quality. Field strength increases linearly with current in the coils (up to a saturation point), and decreases rapidly as the magnet aperture is widened. Large-aperture magnets that transport high-energy beams will use large amounts of energy - easily several kilowatts per magnet. At these power levels, waste heat must be carried away, usually using active water cooling, which adds roughly another 35% to the energy budget as well as making the infrastructure more complex.

Manufacture of accelerator components, in common with all other human-made items, also has environmental impacts. Iron and copper ores are extracted from the ground in mines; refined to usable metals in a processing facility; transported to a factory by sea, road, and rail; extruded and machined to the correct shape; assembled into a complete magnet; and finally, the finished product is transported to the facility where it will be used. At every stage, carbon emissions are generated which depend on the particulars of the process used. We can quantify the levels of these emissions using lifecycle analysis (LCA) techniques. Due to the complexity of the supply chains involved, LCA can be a highly complicated process with many inherent uncertainties. Despite this, we can use LCA to guide decisions about procurement, so that we can ensure that the magnets we buy have the lowest-possible embodied carbon emissions. Steel, for instance, has a wide range of carbon emissions associated with its manufacture, with one study [Hasanbeigi] giving a range of values between 1.08 kgCO$_2$e/kg (Mexico) and 2.15 kgCO$_2$e/kg (China). Here, CO$_2$e is a measure of global warming potential, and combines the global warming impact of CO$_2$ and various other greenhouse gases. Mexico has a particularly low value due to the widespread adoption of electric arc furnaces, which are associated with lower emissions than traditional coke-fired blast furnaces.

Permanent magnets (PMs) offer an alternative to resistive electromagnets. Many accelerators operate at a fixed energy, transporting a beam along a fixed path, which implies that a static magnetic field would be suitable. A Halbach array of permanent magnet blocks can generate any combination of multipole fields (dipole, quadrupole, sextupole, and so on) depending on the configuration of the blocks [Halbach]. This device is remarkably compact: a Halbach quadrupole just a few centimetres across can produce the same field as an electromagnet half a metre in width. Halbach magnets are already used in applications with small apertures and fixed fields (such as drift tube linacs) and have notably been used as beam transport for a complete accelerator, CBETA. The advantages of PM-based magnets are obvious: no energy is expended in the magnet system, no waste heat is generated, and the infrastructure is simpler - no large power supplies, thick current-carrying cables, or water pipes. This all makes a compelling case for PMs as a sustainable solution.

There are of course disadvantages to PM technology. Unlike electromagnets, which can be switched on and off quickly, tuning is not easy. Adding coils to a PM system is relatively inefficient (since PMs have a low permeability), and whilst solutions for mechanical tuning exist [Ghaith], they are a relatively immature technology and do not offer quick adjustment. Temperature variation means that a change of 3°C in ambient temperature results in a field change of 1%, unacceptable for high-precision accelerator applications - though this can be countered using FeNi thermal shunts, which have a positive temperature coefficient. The strong mechanical forces exerted by PMs on ferromagnetic objects lead to a more complex assembly and installation process. Variations in magnetisation between blocks makes field quality more difficult to control. Finally, PMs that are subject to intense ionising radiation will degrade over time and lose their strength. Despite all these downsides, PM technology has been used on accelerators for decades, particularly for undulators and wigglers for light sources, and is now seeing more widespread adoption - many recent fourth-generation light sources have made increased use of PM devices [Shepherd].

Strong PMs are built from SmCo or NdFeB, both of which include rare-earth elements (REEs). REEs are not really 'rare', but are only mined in a small number of locations worldwide, leading to monopolisation and other supply chain issues. As with other raw materials, there is an environmental cost associated with extracting them from the earth. Estimates vary, but the carbon emissions involved in producing REE PMs are weight-for-weight far greater than those involved in producing steel or copper - between 30-158 $kgCO_2e/kg$ for NdFeB produced in China [Bailey]. (This is leaving aside other environmental impact indicators such as eutrophication, acidification, and land use change.) So a Halbach quadrupole, despite its compact size, would have a similar manufacture carbon footprint to the equivalent electromagnet. However, this one-off manufacture footprint is tiny compared with the emissions associated with operating an electromagnet for the typical 10-20 year lifespan of an accelerator, even with the greenest electricity available. This is even true for larger adjustable PM-based devices, which weigh in at a similar size to equivalent electromagnets.

The conclusion is clear: PM systems are a viable replacement for many fixed-field electromagnets used in accelerators, and offer vastly reduced lifetime emissions. As with many emissions-reducing technologies, however, the difficulty lies in the higher upfront cost of such systems. Research institutes often deal with budgets that operate on a yearly cycle, and aim to maximise efficiency of expenditure of public money, and there is little opportunity to purchase systems which offer lower operating costs if the capital costs are much greater than a tried-and-tested technology. Geopolitical issues leading to increased energy costs may go some way to change this, together with a shift in the mindset of many organisations towards a greater focus on environmental sustainability.

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A dipole magnet (left) [Science Photo Library] and a quadrupole magnet (right) [Science Photo Library] A Halbach PM-based quadrupole magnet [Antec]