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PERMANENT MAGNETS FOR ACCELERATORS

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Abstract

Several groups internationally have been designing and building adjustable permanent magnet based quadrupoles for light sources, colliders, and plasma accelerators because of their very high gradients and zero power consumption. There are now examples of widely adjustable PM dipoles too. The ZEPTO project, based at STFC Daresbury Laboratory, developed several highly adjustable PM-based dipole and quadrupole prototypes for CLIC, and is now building a quadrupole to be installed in Diamond to gain experience ahead of the Diamond-2 upgrade. This is a review and comparison of the recent designs globally with comments on the future prospects.

INTRODUCTION

Permanent magnets (PMs), are materials that retain a strong remanent magnetisation after the applied magnetising field is removed. Energy is stored in the material, and a PM can produce a strong field especially when combined with other ferromagnetic elements to form a flux circuit.

Development of PMs is arguably one of the technological success stories of the 20th century [1], with the energy product BH_{max} doubling on average every twelve years thanks to the discovery of ferrites and later SmCo and NdFeB (Fig. 1), the latter being an 'almost ideal' PM material with a high proportion of iron and a relatively abundant rare-earth element. Both Sm_2Co_{17} and $Nd_2Fe_{14}B$ are near their theoretical maxima of 294 kJ/m³ and 512 kJ/m³ respectively. The discovery of new PMs led to technological developments in many other fields, including information storage, transport and energy generation.

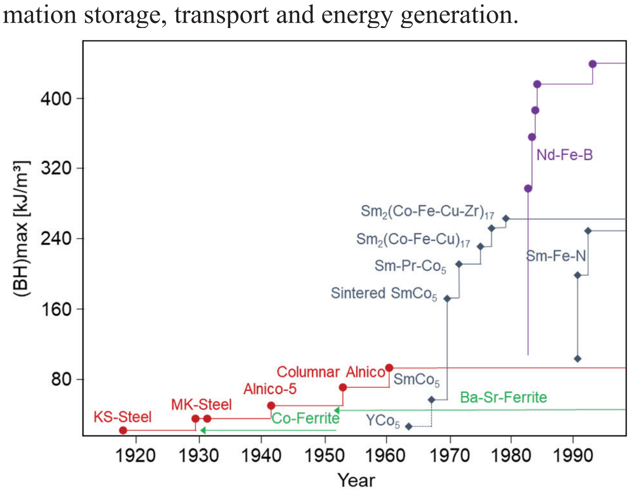

Figure 1: Development of PMs in the 20th century.

In accelerators, a major use of PMs over the years has been undulators and wigglers (insertion devices or IDs) in light sources [2], first proposed by Ginzburg in 1947 and used in storage rings from the 1970s onwards. When short periods and small gaps are required, PMs are usually a better choice for IDs. The Halbach array with four magnets per period gives an enhanced field on one side of each array which combines to give a strong field in the beam tube. These IDs have been extensively written about elsewhere [3] and are not the focus of this paper.

BEAMLINE PM DEVICES

The Halbach array can also be 'wrapped' around a cylinder to create a multipole magnet [4, 5]. Fields from an array of wedge-shaped PMs combine to give a strong field in the magnet centre (Fig. 2). These magnets typically have small apertures, and high gradients can be achieved. The gradient in a Halbach quadrupole is given by:

$$G = 2B_r K \left(\frac{1}{r_i} - \frac{1}{r_e}\right)$$

Here, B_r is the remanent field in the PM, r_i and r_e are the inner and outer radii, and K is an efficiency factor which approaches 1 as the number of segments increases.

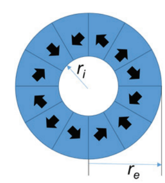

Figure 2: Schematic of a Halbach PM quadrupole, showing the inner and outer radii of the PMs.

Other multipole magnets (e.g. dipoles, sextupoles and combined function magnets) can be produced in this way.

Light source upgrades in recent years have focused on increasing the brightness, which often means a push to smaller apertures. When an electromagnet is scaled down by a factor k, if the current density is kept equal, the field will be reduced by k. In order to restore the field, either the current density or cross-section of the coils must be increased. PM-based magnets do not have this limitation, and this seems to favour the use of PM magnets for lower-aperture devices [6].

Advantages of Permanent Magnets

PM-based magnets require no current to provide a constant field. No large power supplies are required, and no current-carrying cables. No heat is dissipated, and so no water cooling is required (which also eliminates a potential source of vibration). So overall the infrastructure and running costs can be lower than electromagnets, and of course the CO_2 emissions during operation are greatly reduced.

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Disadvantages and Mitigation

Temperature Stability Remanent field B_r changes as a function of temperature. This is a larger effect for NdFeB than for SmCo, with temperature coefficients in the vicinity of -1x10^{-3}/°C and -3x10^{-4}/°C respectively. This effect can be mitigated in a magnet by adding a shunt material with the opposite sign coefficient [6-9]. As the temperature increases, less flux is produced by the PM, but less is shunted away (Fig. 3). A typical shunt material is FeNi, traded as "Thermoflux".

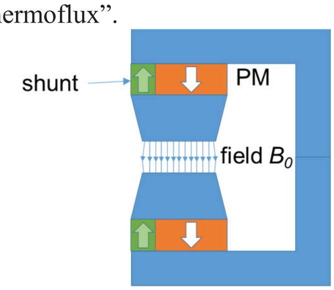

Figure 3: Schematic of a temperature compensation shunt in a PM dipole.

Radiation Impact of a high-energy particle in a PM material can cause a release of energy, leading to nucleation of inverse domains in a PM. Another mechanism is wide-area energy release from a large number of low-energy particles, and this effectively heats up the material.

Radiation damage can be mitigated in a number of ways, and research over several decades has identified many different variables that can have an impact [10-11].

- A higher-coercivity material performs better in a radiation environment, so for instance SmCo would be better than NdFeB.
- Operating at a lower temperature also increases the coercivity; experiments have shown that demagnetisation from 2.5 GeV electrons is reduced by 99% when the temperature is reduced to 140 K compared to room temperature.
- Baking PMs before use gives a small controlled demagnetisation, but can significantly reduce the radiation-induced demagnetisation.
- Altering the magnetic circuit or the shape of the PMs to change the operating point or permeance coefficient $Pc = B/H$. This reduces the demagnetising field seen by the PMs.
- Moving PMs away from the beam can reduce the amount of radiation that the PMs experience. This is potentially much easier to do for beamline magnets than for insertion devices, where the PMs are positioned as close to the beam as possible.

Tolerances A batch of PM blocks will have tolerances on dimensions and magnetisation strength and direction. For Halbach magnets and insertion devices, the field quality is directly influenced by differences between individual PMs. However for beamline magnets, blocks are often made up of individual smaller PMs, and the field quality is set by the shape of steel poles. Tolerances on individual PM blocks may be "smeared out" in this case.

Tuning This is perhaps the most obvious problem in designing PM-based magnets. Coils can be added to a PM-based magnet; however the operating point is in the flat part of the *B-H* curve, so the permeability is the same as free space. Large coils are needed for a relatively small change in field; so if a large adjustment range is needed, it becomes simpler to just replace the PMs with coils. A typical example of a PM dipole with adjustment provided by coils is shown in Fig. 4.

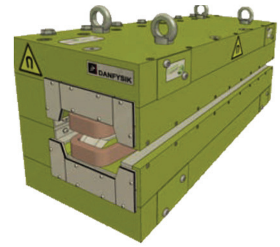
Figure 4: A 1 T dipole manufactured by Danfysik for the ASTRID-2 facility. The coils provide around ±3% of adjustment of the central field.

PMS AT ACCELERATOR FACILITIES

Synchrotron light sources around the world are upgrading to low-emittance lattices to increase their output brightness. In many cases these upgrades involve new PM devices as part of their magnetic lattice.

Sirius

At Brazil's LNLS facility, the Sirius facility requires 20 so-called 'Superbend' magnets (Fig. 5) with a maximum field of 3.2 T at a point in the magnet centre, and long combined function sections either side providing 0.5 T field and 9.5 T/m gradient. Adjustment via 'floating poles' and a control gap in the return yoke provides ±4% of tuning range in both field and gradient.

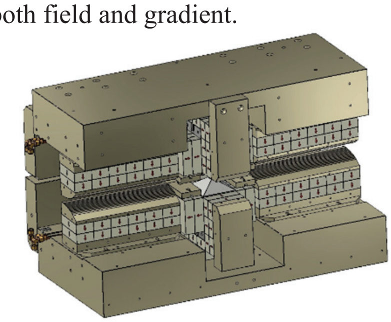
Figure 5: The Sirius facility's 'Superbend' magnet [12].

All the Superbend magnets have now been measured and installed, and at least 10 mA of beam has been circulated in the machine [13].

The ESRF

The "Extremely Brilliant Source" upgrade at the ESRF [6, 14] requires a total of 128 longitudinal gradient (LG) dipoles (Fig. 6), which have all been built using PMs. The dipoles are composed of five modules each with a constant field. The field steps up from 0.17 T to 0.53 T (or 0.64 T); this contributes to a reduced emittance by matching the field to the varying horizontal dispersion.

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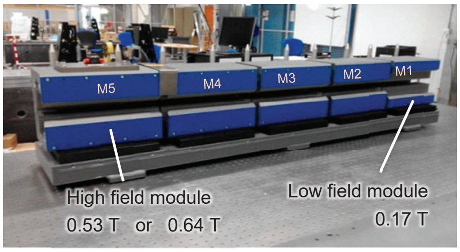

Figure 6: A PM LG dipole for the ESRF EBS upgrade.

Sm_2Co_{17} blocks are used to build the dipoles; all the modules (except the lowest field M1) are constructed identically except with a different number of PM blocks to alter the field. There is no capacity for tuning the dipoles. FeNi "Thermoflux" shunts are used, with a thickness between 0.8-4.5 mm, to bring the residual temperature coefficient down to 10 ppm/°C around room temperature (23°C).

The magnets are installed at the ESRF and commissioning is under way. Stored beam was achieved in December 2019, and first X-rays were produced in January 2020 [15].

Diamond Light Source

Like the ESRF-EBS, the planned upgrade for Diamond has fixed-field LG dipoles; the Diamond-II design [16] requires 96 of these, each with fields ranging from 0.29 T to 0.76 T (Fig. 7). Sm_2Co_{17} blocks are used, with FeNi shunts to compensate temperature variation.

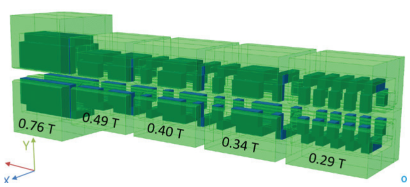

Figure 7. The LG dipole design for Diamond-II [17].

The current design for the combined-function DQ magnets for the storage ring is based on electromagnets; using PM magnets for these is also a possibility.

SPring-8

The SPring-8-II upgrade [18] is again based around PM-based LG dipoles, with a field range of 0.25-0.79 T in each magnet [19]. Tuning of the field is achieved by including a movable outer plate in the design (Fig. 8). A 400 mm long prototype has been built using NdFeB blocks, with three modules producing a 0.2-0.55 T field. FeNi magnetic shunts with thicknesses between 5-18 mm reduce the field variation with temperature down to 5-10 ppm/°C. A 'window' in the magnet backleg provides space for an NMR probe for long-term field observation.

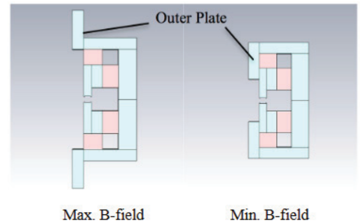

Figure 8: Cross-section of the SPring-8-II LG dipole prototype, showing outer plates used to provide field tuning.

R&D into a PM-based septum magnet (Fig. 9) has also taken place at SPring-8 [20]. This could potentially replace a single multi-kilowatt pulsed septum magnet. The baseline field is 1.2 T, and movable steel shunt plates provide a 2% adjustment range. The 5.5 mm thick FeNi magnetic shunt reduces the temperature variation down to around 1 ppm/°C. The 7 mm thick septum plate and counter-field PMs reduce the field seen by the stored beam down to almost zero.

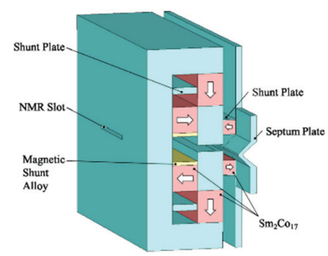

Figure 9: Schematic of a PM-based septum magnet for SPring-8-II.

Prototypes of the LG dipole and the septum magnet have been built and tested; they all meet the specifications.

Table 1 shows a summary of the PM dipoles used in the light source upgrade projects mentioned in this paper.

CBETA

CBETA is a 4-pass energy recovery linac (ERL) machine with a compact non-scaling FFAG lattice. This design is based entirely on PM-based magnets, with 216 fixed-field quadrupole and combined-function Halbach magnets [21]. Each magnet is composed of 16 PM wedges, with larger wedges being used for the DQ magnets (Fig. 10).

Table 1: Summary of PM Dipoles Used in Light Source Upgrade Projects

Parameter	**Sirius**	**ESRF-EBS**	**Diamond-II**	**SPring-8-II**
Energy	3 GeV	6 GeV	3.5 GeV	6 GeV
Lattice	5BA	7BA	6BA	5BA
Emittance	250 pm	135 pm	160 pm	149 pm
Number of dipoles	20	128	96	168
Dipole strength	0.5 T, 3.2 T	0.17-0.64 T	0.29-0.76 T	0.25-0.79 T
Gap	11 mm	25 mm	25 mm	25 mm
Adjustment range	±4%	None	None	Few %
Temperature stability	Not specified	10 ppm/°C	TBD	5-10 ppm/°C

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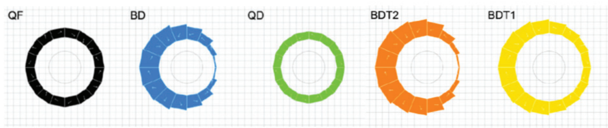

Figure 10: 2D outlines of the five CBETA magnet types.

The CBETA magnets have lengths between 122-133 mm, with gradients of ±11 T/m and bend fields of 0.3 T. Apertures are 80-98 mm.

To correct field errors arising from PM block tolerances, steel rods of varying lengths were inserted into a 3D printed insert just inside the magnet aperture (Fig. 11). This novel field correction method reduced the overall field errors down to an RMS value of 2.6×10^{-4}.

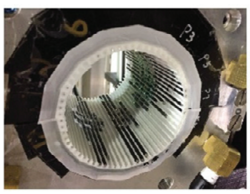
Figure 11: Field error tuning rods used in CBETA magnets.

QUAPEVA

At the COXINEL laser-plasma experiment [22], strong small-aperture quadrupoles are needed to focus a highly-divergent plasma-accelerated electron beam. SOLEIL have developed a highly-tunable PM quadrupole [23]. A central hybrid Halbach array is combined with rotating PM cylinders in the outer part of the magnet (Fig. 12), controlled by four independent motors. The magnet aperture is 12 mm and the adjustment range is 100-200 T/m. The early prototype had some issues with magnetic centre movement during adjustment, but this is reduced to around ±10 µm in the later models. A triplet of QUAPEVA magnets has been installed on the COXINEL beamline [24].

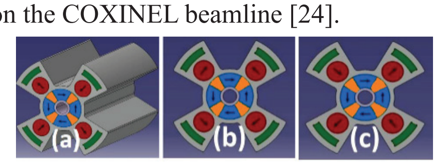

Figure 12: Adjustment principle of the QUAPEVA magnets; (a) maximum, (b) middle, and (c) minimum gradient.

THE ZEPTO PROJECT

In recent years, ASTeC and CERN have been collaborating on a project to develop highly tunable PM-based quadrupoles, aimed at the specifications for CLIC's drive beam decelerator (DBD). The motivation was to find an alternative to the 13.5 MW of electrical power required for 41,848 quadrupoles in the DBD line.

The ZEPTO (ZEro-Power Tunable Optics) concept is based around fixed steel poles and large PMs which are moved vertically, altering the magnetic circuit and provide a wide adjustment range. Two prototypes were designed, built and tested at DL and CERN – the first [25, 26] was designed to reach a large maximum gradient (60 T/m), sufficient for the high-energy end of the DBD, and the second [27, 28] to give a wide tuning range. In the first, tuning is achieved by introducing a gap between the PMs and the poles; the second moves the PMs perpendicular to the magnetisation axis and shifts the flux to a secondary outer circuit. In each case, the PMs are controlled by a single motor through a set of gearboxes and dual-threaded ballscrews.

Measurements of the ZEPTO quadrupoles indicated that they performed well against the CLIC specifications. One issue that arose was a small shift in the magnetic centre as the magnets were tuned from low to high strength; this was attributed to weakly ferromagnetic rails used in the motion system, which were not vertically symmetric.

A PM dipole magnet was also built as a prototype for the dipoles in the drive beam turnaround loops [29, 30]. This operates on similar lines, with a very large PM block sliding horizontally out in the dipole backleg to give a tuning range from 0.46-1.1 T. This very large block proved to be quite difficult to handle since the magnetic forces were so large; however the magnet performed very well and meets the specifications in terms of field quality and strength.

A third ZEPTO quadrupole magnet is currently under construction at Daresbury Laboratory. This one will be installed on Diamond's BTS transfer line, as a drop-in replacement for an electromagnetic quadrupole, with the aim of demonstrating that this PM technology can be used on an operating user facility. This is a further step towards commercialisation of our innovative PM technology. The concept is similar to ZEPTO-Q2, with two PMs moving vertically between a primary and secondary circuit for a large adjustment range. Two motors are used to ensure the magnet centre stays fixed during adjustment. SmCo blocks are used for improved temperature stability and radiation resistance. The magnet is splittable horizontally to enable installation around an existing vacuum chamber.

Table 2: Comparison of ZEPTO Magnet Parameters

Parameter	ZEPTO-Q1	ZEPTO-Q2	ZEPTO-D1	ZEPTO-Q3
Aperture	27.2 mm	27.6 mm	42 mm	32 mm
Magnet length	230 mm	190 mm	500 mm	300 mm
Field / gradient range	15-60 T/m	4-35 T/m	0.46-1.1 T	0.5-19 T/m
PM block size	18x100x230 mm	37.2x70x190 mm	500x400x200 mm	68x35.5x300mm
Number of blocks	4	2	1	2
Movement range	64 mm	75 mm	355 mm	90 mm
Good field region	±0.1%, 23 mm	±0.1%, 23 mm	±0.1%, 40 mm (H)	±0.1%, 20 mm
Measured centre shift	100 µm	80 µm	Zero	N/A

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Design of ZEPTO-Q3 is complete, and construction and installation will take place in late 2020. Table 2 shows a summary of the parameters of all four ZEPTO magnets.

CONCLUSIONS

PM-based magnets are finding increasingly widespread use as beamline magnets in accelerator facilities worldwide, particularly where compact magnets and high fields are required. They have many advantages over traditional electromagnets in terms of resource use and infrastructure and operating costs. There are several well-documented issues in using PMs, for instance radiation hardness, temperature stability, tuning, and block-to-block variations. However, these can be mitigated using several innovative techniques. Coils can be combined with PM magnetic circuits for a few per cent adjustment, or larger tuning ranges can be achieved using mechanical movement. Increasing use of this technology will no doubt lead to further innovations, as we have seen in the field of insertion devices – where recent innovation such as cryogenic PM undulators have led to further increases in performance. As we transition to a greener economy in the next decade, low-emission technologies like PMs will become increasingly important.

REFERENCES

[1] J. M. D. Coey, "Hard magnetic materials: a perspective", *IEEE Trans. Mag.*, vol. 47, no. 12, pp. 4671-4681, Dec. 2011. doi:10.1109/TMAG.2011.2166975

[2] A. L. Robinson, "X-Ray data booklet", https://xdb.lbl.gov

[3] J. A. Clarke, "The science and technology of undulators and wigglers", Oxford, UK: Oxford University Press, 2004.

[4] K. Halbach, "Design of permanent multipole magnets with oriented rare earth cobalt material", *Nucl. Instrum. Methods*, vol. 169, pp. 1-10, 1980. doi:10.1016/0029-554X(80)90094-4

[5] C. Benabderrahmane and J. Chavanne, "Review of permanent magnet technology for accelerators", presented at IPAC'17, Copenhagen, Denmark, May 2017, paper THYB1, unpublished.

[6] J. Chavanne, "Permanent accelerator magnets for light sources", presented at the 5th ESSRI Workshop, PSI, Nov. 2019, unpublished.

[7] Vacuumschmelze material data, https://vacuumschmelze.com/Products/Permanent-Magnets

[8] F. Bødker *et al.,* "Permanent magnets in accelerators can save energy, space and cost", presented at IPAC'13, Shanghai, China, May 2013, paper THPME001, pp. 3511-3513.

[9] S. H. Kim and C. Doose, "Temperature compensation of NdFeB permanent magnets", presented at PAC'97, Vancouver, Canada, May 1997, paper 2P001, pp. 3227-3229.

[10] A. J. Samin, "A review of radiation-induced demagnetization of permanent magnets", *J. Nucl. Mat.*, vol. 503, pp. 42-55, May 2018. doi:10.1016/j.jnucmat.2018.02.029

[11] B. J. A. Shepherd, "Radiation damage to permanent magnet materials: a survey of experimental results", CLIC Note 1079, May 2018.

[12] J. Citadini, L. N. P. Vilela, R. Basílio and M. Potye, "Sirius – details of the new 3.2T permanent magnet superbend", presented at MT-25, Amsterdam, The Netherlands, Aug 2017, paper Tue-Af-Po2.02-07.

[13] L. Liu, "Sirius commissioning results", presented virtually at IPAC'20, May 2020, paper MOVIR06, this conference.

[14] G. Le Bec *et al.*, "Magnets for the ESRF diffraction-limited light source project", *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1-8, June 2016. doi:10.1109/TASC.2015.2510402

[15] ESRF EBS blog, https://ebs.esrf.fr

[16] Diamond-II upgrade CDR and science case, https://www.diamond.ac.uk/Home/About/Vision/Diamond-II.html

[17] A. Shahveh, presented at Diamond-II MAC, Feb. 2020, private communication.

[18] H. Tanaka, "Upgrade strategy and development status of accelerator system at SPring-8/SACLA", PSI seminar, Dec. 2019, https://indico.psi.ch/event/8362

[19] T. Taniuchi *et al.*, "R&D of permanent dipole magnet for SPring-8-II", in *PASJ'16*, Chiba, Japan, Aug. 2016, paper MOP109 (in Japanese).

[20] T. Taniuchi *et al.*, "DC septum magnet based on permanent magnet for next-generation light sources", *Phys. Rev. Accel. Beams*, vol. 23, p. 012401, Jan. 2020. doi: 10.1103/PhysRevAccelBeams.23.012401

[21] S. Brooks *et al.*, "CBETA permanent magnet production run", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 4318-4321. doi:10.18429/JACoW-IPAC2019-THPTS088

[22] D. Oumbarek Espinos *et al.*, "Skew quadrupole effect of laser plasma electron beam transport", *Appl. Sci.* vol. 9, no. 12, p. 2447, Jun. 2019. doi:10.3390/app9122447

[23] F. Marteau *et al.*, "Variable high gradient permanent magnet quadrupole (QUAPEVA)", *Appl. Phys. Lett.*, vol. 111, no. 25, p. 253503, Nov. 2017. doi:10.1063/1.4986856

[24] A. Ghaith *et al.*, "Tunable high gradient quadrupoles for a laser plasma acceleration based FEL", *Nucl. Instrum. Methods*, vol. 909, pp. 290-293, Nov. 2018. doi:10.1016/j.nima.2018.02.098

[25] B. J. A. Shepherd *et al.*, "Tunable high-gradient permanent magnet quadrupoles", *J. Inst.*, vol. 9, T11006, Nov. 2014. doi:10.1088/1748-0221/9/11/T11006

[26] B. J. A. Shepherd *et al.*, "Prototype adjustable permanent magnet quadrupoles for CLIC", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPME043, pp. 3606-3608.

[27] B. J. A. Shepherd *et al.*, "Novel adjustable permanent magnet quadrupoles for the CLIC drive beam decelerator", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4004204, Mar. 2012. doi:10.1109/TASC.2012.2191632

[28] B. J. A. Shepherd *et al.*, "Design and measurement of a low-energy tunable permanent magnet quadrupole prototype", in *Proc. IPAC'14*, Dresden, Germany, June 2014, pp. 1316-1318. doi:10.18429/JACoW-IPAC2014-TUPRO113

[29] A. R. Bainbridge *et al.*, "The ZEPTO dipole: zero power tuneable optics for CLIC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 4338-4340. doi:10.18429/JACoW-IPAC2017-THPIK105

[30] A. R. Bainbridge *et al.*, "Measurement report on the prototype ZEPTO dipole magnet for CLIC", presented at IMMW21, Grenoble, France, June 2019, unpublished.