HIGH GRADIENT PM TECHNOLOGY FOR ULTRA-HIGH BRIGHTNESS RINGS

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Abstract

Permanent magnets have long been major components in accelerator-based light sources, particularly as a part of insertion devices. However, their use as main lattice magnets (dipoles, quadrupoles) has been so far somewhat limited. The present trend towards small magnet apertures, exemplified by various multibend achromat designs currently under commissioning or design/construction opens up the discussion once more on the large-scale use of permanent magnets as a means to achieve extremely high gradients in future diffraction-limited storage rings. This paper will review the current R&D programs on the use of permanent magnets in the lattice of high brightness storage rings.

INTRODUCTION

Projects of ultra-small emittance storage rings have been launched around the world. The Max-IV project in Sweden is the first storage ring of this new generation [1]: a 330 pm·rad emittance at 3 GeV is targeted with a 7-bend achromat lattice and 40 T/m gradients. The European Synchrotron Radiation Facility – Extremely Brilliant Source (ESRF-EBS) project, in France [2], aims to reach an emittance of135 pm·rad at 6 GeV, while the Advanced Photon Source Upgrade (APS-U) targets 70 pm·rad at 6 GeV [3]. The ESRF-EBS project is in the procurement phase and the APS-U is in an advanced development stage. In these two projects the quadrupole gradients reach almost 100 T/m, which appears to be the upper limit of standard electromagnet technology. Such high gradients have been enabled by the shrinking of the vacuum chamber aperture: in all these projects, the magnet bore diameter is about 25 mm.

The theoretical minimum emittance obtainable on an electron storage ring has been presented in various papers [4, 5]. It appears that i) ultra-low emittance machines should have an increased number of (small angle) dipoles, and ii) the horizontal beta function should reach a minimum value inside the dipoles. The second statement implies either increasing the circumference of the ring for inserting focusing elements with standard gradients, or increasing the gradients. It should be noted here that the highest gradient magnets have been developed for upgrading rings with existing buildings and beamlines. Generally speaking, it seems more cost-efficient to increase the magnet gradients than to increase the length of the rings.

Focusing magnets used in ultra-high brightness rings are subject to specific design constraints. They should be high gradient and compact, as mentioned above. The gradients should be reasonably tunable, e.g. within ±5 % for the high gradient quadrupoles of the ESRF-EBS. The homogeneity of the gradient should be sufficient to preserve a acceptable dynamic aperture and lifetime. Synchrotron radiation must escape from the ring: a slot free of magnetic material should be available around the horizontal symmetry plane. Finally, storage ring magnets must be reliable, cost effective, and low in power consumption.

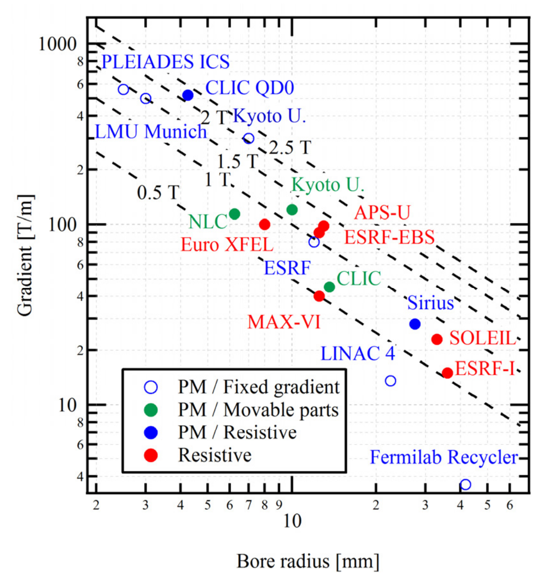

Figure 1: Examples of quadrupole gradients vs magnet bore radius for different technologies, including resistive magnets [12, 13], hybrid PM/resistive magnets [8, 11], tunable PM magnets with movable parts [10, 14-16] and fixed gradient PM magnets [6, 9, 17-19]. The dashed lines indicate the equivalent pole tip field defined as the radius times the gradient.

Figure 1 shows the gradient of a few examples of quadrupoles of different technologies. Ultra-high gradients are reached at bore radii smaller than 5 mm, which seems not compatible with the light source storage ring constraints mentioned above. All devices with a radius below 10 mm have been designed for linear accelerators [6-8]. At the opposite corner of the figure, the quadrupoles of the Fermilab Recycler are low gradient, low field and large aperture [9]. This accelerator should be mentioned as the first large scale ring with magnets entirely energised with ferrite PM blocks. The quality of the magnetic field, i.e. the gradient homogeneity, does not appear in the figure. It should be noted that the only magnets with field quality suitable for storage rings are below the 1.5 T line. Tunable, moderate gradient PM Quadrupoles (PMQs) prototypes have been developed for large scale applications like CLIC [10] or Sirius [11]. The

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main goals of these developments was power saving and, in the case of CLIC, to avoid themal dissipation issues in the accelerator tunel. A PM quadrupole prototype was built at the ESRF [18]. Although its fixed 85 T/m gradient at 12 mm radius is quite modest, the main goal of this development was to improve the field quality of PM quadrupoles.

Up to now, the main application of PM in accelerators is the Insertion Devices (IDs). IDs are typically built with hundreds of PM blocks generating a sinusoidal magnetic field within a gap. Such devices produce a strong field gradient along the longitudinal axis, e.g. about 140 T/m for a standard 35 mm period undulator at 11 mm gap, and up to 460 T/m for a 15 mm period Cryogenic Permanent Magnet Undulator (CPMU) operated at 4.5 mm gap. The tuning of the field is usually done by changing the gap with motorized magnet girders [20-22]. In each cell of the ESRF-EBS lattice, four out of seven dipoles will have a longitudinal gradient. All of these low field (up to 0.67 T) dipoles will be built with permanent magnets [23]. Here, the permanent magnets have the advantage of being very compact, simple and with zero power consumption.

The next section presents the Rare Earth PM materials, which are commonly used in accelerator applications. A few high gradient quadrupole designs are reviewed in section 3, while section 4 is dedicated to the gradient tuning. The last section sketches perspectives for PM quadrupole R&D.

RARE EARTH PM MATERIALS

PM materials used for high gradient quadrupole magnets are obtained with powder metallurgy techniques. An alloy of rare earth material and transition metal is reduced in monocristalline grains; these grains are aligned by a strong magnetic field during the powder compaction, and the material is sintered and annealed. The materials obtained with this method are strongly anisotropic and can be magnetized along their so-called easy-axis, which is the average axis of the grains.

The magnetic field in a PM material is $B = \mu_0(H + M)$, where μ_0 is the vacuum permeability, H is the magnetic field strength and M is the magnetization. The PM materials are characterized by their remanent magnetization M_R or by their remanent field B_R and by their intrinsic coercive field H_{cJ}, as shown in Figure 2. The materials of interest have a strong B_R, which means a strong magnetization, and strong H_{cJ} to avoid irreversible demagnetization.

Two types of PM materials are used for high gradient PM quadrupoles: Samarium-Cobalt (SmCo) and Neodymium-Iron-Boron (NdFeB). The main magnetic properties of these materials are summarized in Table 1. The high B_R materials NdFeB are unfortunately the low H_{cJ} ones, and the 1.4 T magnets cannot be used in room temperature accelerator applications due to their limited coercivity.

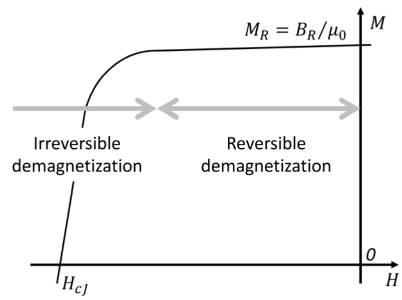

Figure 2: M(H) magnetization curve of a permanent magnet material. The material should be used in the linear, reversible region to avoid demagnetization.

Table 1: Properties of PM Materials at Room Temperature

Material	B_R [T]	H_{cJ} [MA/m]	dB_R/dT [10^{-3}/K]
Sm_2Co_{17}	1.05−1.15	0.8−2.1	−0.3
NdFeB	1.08−1.43	0.8−3	−1

The magnetization of PM materials is temperature dependent: in lattice magnet application, thermal effects must be compensated. The most common thermal compensation method consists in shunting a part of the flux of the magnets with a highly temperature-dependent material [24]: low Curie temperature FeNi alloys have been specifically developed for this purpose [25]. For SmCo material, the volume of the thermal compensation shims is about 5 to 10 % of the PM volume. The FeNi shim volume would be three times larger for NdFeB material, which seems impractical. If NdFeB material is used for lattice magnets, the temperature effects may need be active correction(by coils, by gap motions, etc.) or the magnet temperature should be controlled to better than 0.1°C at room temperature.

The material of PM quadrupoles must resist radiation damage during the lifetime of an accelerator, i.e. 20 to 30 years. A faster than expected field decay has been observed on Strontium ferrite magnets installed at Fermilab [26]. Operational experience with IDs and PM irradiation in test setups have shown that Sm_2Co_{17} is the hardest material at room temperature [27-32]. NdFeB magnets can be safely used if their coercive field is sufficient, i.e. if $H_{cJ} \geq 2.4$ MA/m approximately; the remanent field of these magnets is typically in the range 1.1 – 1.2 T. Photo-induced neutrons generated during electron beam losses are suspected to produce thermal spikes in the PM material, leading to the observed radiation damage [33, 34].

The coercive and the remanent fields of NdFeB magnets strongly increase at low temperature (Fig. 3). The optimal temperature for NdFeB magnets is about 150 K [21, 35, 36].The spins of the magnetic grains start to reorient and the remanence decreases [37, 38] at 135 K; the relative permeability increases rapidly below 150K, leading to a lower magnetic field. Praseodymium-Iron-Boron (PrFeB) magnets and hybrids Pr/NdFeB can be used at lower temperature without showing a spin reorientation transition, which make them attractive for high gradient and highly radiation-resistant magnets [39]. The use of such cryo magnets has been demonstrated for ID applications and one can foresee it will become an important R&D topic for high gradient lattice magnets.

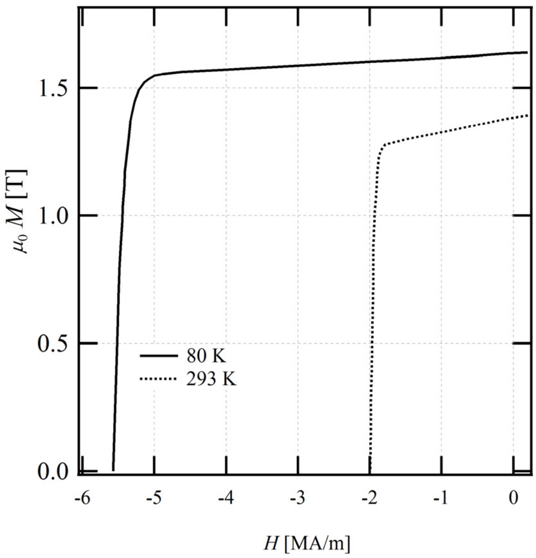

Figure 3: M(H) curve of a Pr(0.8)Nd(0.2)$_2$Fe$_{14}$B material with dysprosium grain boundary diffusion [23, 39].

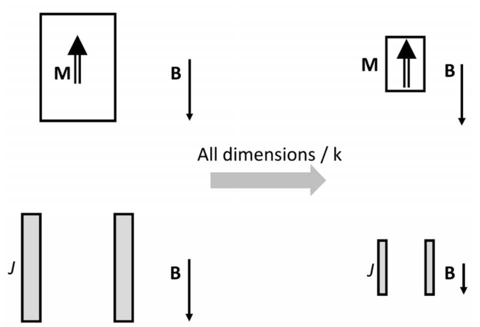

Figure 4: Effect of a scaling factor k applied to a permanent magnet (top) and to an electromagnet with current density J (bottom).

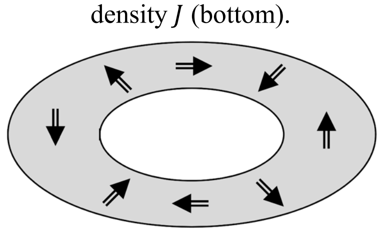

Figure 4: Halbach quadrupole with elliptical aperture.

PM QUADRUPOLES

The field of a permanent magnet remains unchanged when all of its dimensions are divided by a factor k (Figure 4); the same transformation applied to an electromagnet lead to a k times smaller field while preserving the same current density in the conductors. The gradient of a PM quadrupole scales with $1/k$: PM are particularly suitable for small, high gradient devices. For instance, at similar gradient and aperture, the PM prototype built at the ESRF is about ten times lighter than its resistive counterpart [13, 18].

In the early 1980's, K. Halbach presented a Pure Permanent Magnet (PPM) design method for high field and high gradient multipoles [40]. Halbach magnets have been used for various applications, such as pure permanent magnet undulators [41], storage ring quadrupoles [42] and final focus systems [6]. The gradient produced by a Halbach quadrupole is

$$G = 2\frac{B_R}{r_0}\left(1 - \frac{r_0}{r_1}\right)K,$$

where r_0 and r_1 are the inner and outer radii and $K \approx 0.9$ for a reasonable number of PM segments. This result is for a circular aperture: the gradient can be increased by almost 20 % if the magnet aperture is elliptical, with semi axis ratio $b = a/2$ [43] (Figure 4). Elliptical apertures are convenient for light source storage rings, in which the beam is elliptical rather than round. The analytical results given by Halbach are for infinitely long, perfectly rigid magnets (i.e. with relative permeability $\mu_R = 1$): the finite length and magnetic susceptibility of the magnets bring higher order multipole errors [41]. These errors can be corrected with a numerical optimization of the magnet blocks.

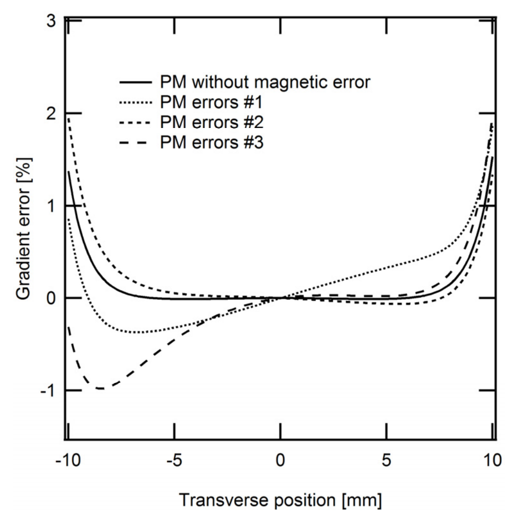

Figure 5: Homogeneity of the integrated gradient for a Halbach quadrupole with a 15 mm radius, 25 mm magnet thickness and 300 mm length. The reference curve (solid) is computed for Sm$_2$Co$_{17}$ magnets without dispersion in remanence in magnetization axis. The other curves are random samples assuming $\sigma_M = 1$ % for magnetization dispersion, $\sigma_{axis} = 0.8°$ for easy axis dispersion and $\sigma_{Position} = 35\ \mu m$ for the magnet position. The magnetization within the magnet is assumed to be homogeneous, which is usually not the case. All the curves have been computed with Radia [44, 45].

Almost four decades after Halbach's publication, storage rings are not filled with PPM multipoles. This is explained by a few issues: the relatively poor homogeneity of the field gradient brought by the PM tolerances (Figure 5), the extensive shimming needed for field corrections [17], and the impossibility of tuning the gradient. The PM blocks located in the horizontal symmetry plane are exposed to radiation damage and do not allow the synchrotron radiation to escape; this issue is mitigated by the possibility to numerically optimize "quasi-Halbach" structures without material at this location.

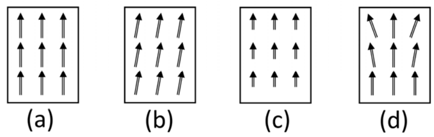

Figure 6: Typical PM block errors. (a): ideal block, (b): axis angle error, (c): magnetization error, (d): magnetization inhomogeneity.

The flaws of the PM blocks appears to be a major obstacle in the development of PPM storage ring quadrupoles. Figure 6 shows typical errors encountered on PM blocks. Real blocks usually present a superposition of three types of errors: errors on the magnitude of the magnetization, errors on the direction of the magnetization, and magnetization inhomogeneities. The specifications of the high quality magnets used for ID assemblies are ly$|\Delta M/M| \leq 0.015$, $|\Delta\alpha| \leq 1.5°$ and $|\Delta\beta| \leq 1.5°$ where $\Delta\alpha$ and $\Delta\beta$ indicate the error in the magnetic moment angles. The magnetization inhomogeneities are usually tested by comparing the magnetic field on both sides of the magnet. The specifications indicated above imply the production of more magnets than necessary and the rejection of some of them.

As mentioned in the previous section, the magnetic polarization of PM blocks suitable for accelerators is about 1.1 T at room temperature and may reach 1.6 T at cryogenic temperatures. Higher polarization can be obtained with soft magnetic material such as pure iron ($\mu_0 M = 2.15$ T) or cobalt-iron alloys ($\mu_0 M = 2.35$ T for a 49% Fe, 49% Co, 2% V). Figure 7 shows schematically the structure of hybrid quadrupoles with iron poles magnetized by PM blocks. High gradient magnet prototypes with iron or cobalt-iron poles have been built for final focussing applications [8, 16].

Hybrid high gradient magnets can be obtained by inserting saturated cobalt-iron poles in a Halbach quadrupole, as shown in Figure 7a. A 300 T/m gradient at 7 mm bore radius has been obtained with a similar design [19]. The homogeneity of the field was not as good as expected, with normalized sextupole and octupole components of about 0.5 % of the quadrupole term at 4 mm radius.

In Figure 7a, the poles are independent to each other, which makes their accurate positioning delicate. If one assumes the position of the poles must not rely on the mechanical tolerances of the PM blocks, the poles can be maintained on the sides or on their back. An alternative design has been developed for the CLIC final focussing magnet, as shown in Figure 7b. The four poles are linked with a ring and are a single part made with wire erosion of a cobalt-iron block. The magnetic flux leak through the linking ring is limited by the saturation of the material, leading to a gradient decrease of about 4 %. In terms of integrated gradient per magnet insertion length, this system can reasonably compete with the Figure 7a solution, in which the length of the PM blocks should be smaller than the total magnet length, for maintaining the poles and positioning them. A 520 T/m gradient at 4.125 mm bore radius was reached with a similar NdFeB device coupled with resistive coils [8].

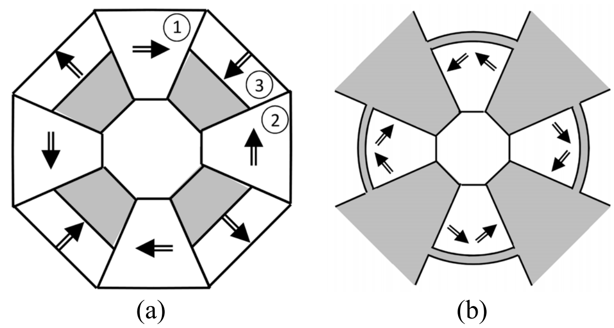

Figure 7: Sketches of strong hybrid PM quadrupole with poles in soft material (in grey), following [19] (a) and [8] (b). In (a), different variants are possible, with or without materials at positions 1, 2 and 3.

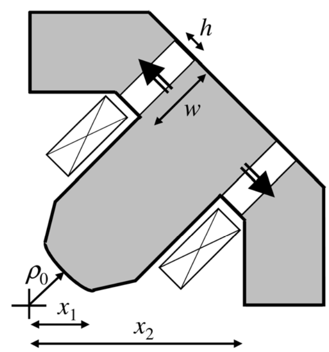

Figure 8: Moderate gradient, hybrid PM-electromagnetic quadrupole [11].

GRADIENT TUNING

The tuning range specifications of the ESRF-EBS are shown in Table 2 [2]. Some field tuning is required for most magnets except dipoles; the quadrupole gradients should be tunable within ±5 % for lattice optimization.

Table 2: Tuning Range of the ESRF-EBS Magnets

N-poles	2	4	6	8
Tuning range [%]	0	±5	±40	−25/+50

Let us consider the hybrid PM-electromagnetic quadrupole shown in Figure 8. This magnet is a low power, moderate gradient quadrupole rather than a high gradient magnet, but an analysis is instructive. At low excitation (i.e. if the iron is not saturated), the gradient is [11]

$$G\left\{\frac{{\rho_0}^2}{2} - \frac{{x_1}^2}{w}h\left(\frac{1}{2} + \frac{x_2}{x_1 - x_2}\ln\frac{x_2}{x_1}\right)\right\} \approx \mu_0(NI + Mh).$$

The minimization of the PM volume at gradient G_0 leads to

$$h \approx \frac{\rho_0{}^2 G_0}{\mu_0 M}$$

and

$$w \approx \frac{x_1{}^2 G_0}{\mu_0 M}\left(\frac{2x_2}{x_2 - x_1}\ln\frac{x_2}{x_1} - 1\right).$$

The gradient $G = G_0 + \mu_0 NI/\rho_0{}^2$ should be compared to the gradient $G = 2\,\mu_0 NI/\rho_0{}^2$ obtained with an electromagnet: both magnets need the same current to reach a $2G_0$ gradient. The current needed to trim a PM quadrupole within a ±5 % tuning range is ±10 % of the current of an electromagnet with the same aperture: this solution is very efficient for limited tuning ranges. The gradient of the prototype described in [11] can be tuned within ±15 %.

The magnetic field of IDs is usually tuned by changing their gap. Similarly, the gradient of PM quadrupoles can be modified by moving mechanical parts of the magnet, as shown in Figure 9 [10, 14, 16, 46]. No current is needed with these designs, which is attractive for low power applications. An almost 100 % tuning range can be reached, which is not possible with trimming coils installed on PM quadrupoles. Magnetic centre motions have been observed on most of these devices and appear to be an important R&D issue; overall centre shifts ranging from 20 to 100 µm were measured depending on the designs. Radiation damage of the position encoders is another possible issue. Such damages are frequently observed on IDs.

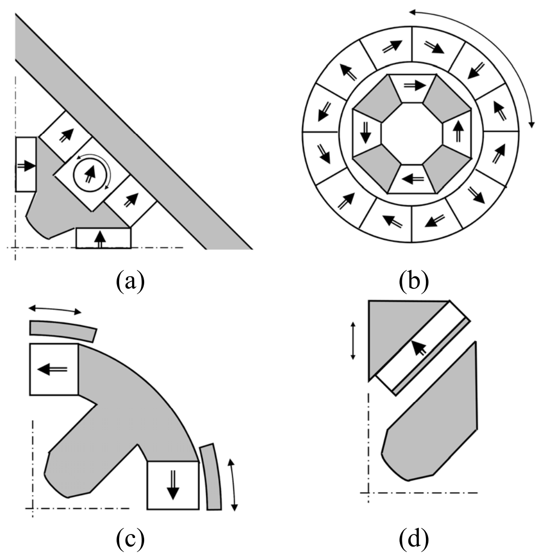

Figure 9: Gradient tuning by motions of mechanical parts. (a): rotation of a cylindrical PM block [14]; (b): rotation of the outer part of the magnet [16]; (c): rotation of iron shims [46]; (d) vertical motion of the PM block and the upper part of the yoke [10].

CONCLUSION & PERSPECTIVES

High gradient PMQs can potentially enable the development of ultra-high brightness storage rings. The technology is not yet mature enough for large scale installation but is being developed by different groups. Three main development axes are clearly identified: the improvement of the PMQ gradient homogeneity, the increase of the gradient, and the tuning of the gradient.

The gradient homogeneity of PM quadrupoles is frequently an issue. A few difficulties are encountered, e.g. the imperfections of the PM blocks, the positioning of the poles, which are usually not built as a single part, and the moving parts if the gradient is mechanically tuned. The undulator builders learned that the imperfections of the magnets and the mechanical parts can be "shimmed" if not avoided. The same approach could be fruitful for high gradient PM quadrupoles, if the magnet design made the shimming easy and fast. Different shimming schemes are possible, e.g. magnet displacements [17] or machining of pole extremities [18]. Above all, the shimming of PM quadrupoles must be made compatible with series production.

Up to now, Cryogenic Permanent Magnet Undulators (CPMUs) compete with superconductive undulators; CPMUs are in operation in various light sources. The development of in-vacuum Cryogenic Permanent Magnet Quadrupoles (CPMQs) is expected to start in the coming years and would enable lower magnetic apertures and higher fields. Reaching a reasonable gradient homogeneity at low temperature on a CPMQ will require an efficient shimming method. The measurement and the alignment of such magnets is also a challenge.

Whatever the technology used, PMQs for storage ring applications will require compact and reliable gradient tuning systems, resistant to radiation damage and with a minimized effect on the magnet alignment and field quality.

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