Superconducting undulators: permanent magnets after all

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Undulators are the key functional unit for providing brilliant x-ray radiation, e.g. in storage rings and free-electron lasers. By its spatial periodicity, the magnetic field of the undulator leads to an oscillating movement of the bypassing electrons, by which high-energy photons are emitted. The quality and brilliance of an undulator are mainly determined by its field amplitude B_0, the period length λ_u, and the magnetic gap in which this field is provided. Strong magnetic fields with short periodicity and small gaps are needed for high-quality undulators.

The very first undulators were built in the 1950s by Motz *et al* [1] from electromagnets with iron yokes. Due to limitations in applicable current in the individual coils, B_0 and minimum λ_u were rather limited. Further improvement was only possible with strong permanent magnets or superconducting coils. The former, permanent magnet undulators (PMUs) and their improved, yet more complex cryogenic versions, CPMUs [2], were realistic only after the advent of rare-earth-based hard magnets such as Sm–Co and Nd–Fe–B compounds, and had been influenced strongly by concepts of Halbach [3]. The latter, superconducting undulators (SCUs), had for a long time the drawback of being highly expensive and not too practical due to the low temperatures needed for the then-available low-T_c superconductors. Nevertheless, with Nb–Ti SCUs, B_0 values above 1.5 T have been achieved, however with periodicities not below 15 mm. While PMUs are standard in storage rings to date and often serve as a reference, SCUs regained strong interest in the last two decades, also due to the development and improvement in high-temperature superconducting (HTS) wires and tapes and the possibility of avoiding liquid He temperatures [4]. Indeed, such high-temperature SCUs have been developed since 2014 in Los Alamos [5], Argonne [6], Seoul [7], Beijing [8], and Karlsruhe [9, 10]. The achievable field B_0 naturally depends on operating temperature besides gap and periodicity, where the performance at 4 K is comparable to Nb-Ti SCUs while much more cost-effective higher temperatures, even 77 K, are possible on the cost of lower B_0 values.

Already nearly twenty years ago, a different kind of SCUs was proposed by Tanaka *et al*, namely using HTS bulks as magnets in planar configuration [11] or as staggered arrays [12].

Keeping in mind that all analogies have their limits, one could regard HTS bulks [13] as counterparts to ferromagnets. Both show a remanent magnetization in the direction of a sufficiently strong previously applied field unless a certain temperature is exceeded, the field-dependent irreversibility temperature for HTS bulks or the Curie temperature for ferromagnets, although usually on a somewhat different temperature scale. There are distinct differences though: While the magnetic entities in ferromagnets, the domains, are already present in the virgin state and rearranged during magnetization by rotation and growth processes, their analogues in HTS bulks, the flux lines, are created and trapped by the magnetization process itself, a necessity for possible stable levitation in other applications. Furthermore, the maximum achievable field is a material constant for ferromagnets, while for HTS bulks it is an extrinsic quantity proportional to sample size and critical current density. Consequently, record remanent fields of more than 17 T were achieved with HTS bulks [14] (later paralleled by stacked-tape samples [15, 16]), which is around an order of magnitude larger than Nb–Fe–B permanent magnets and mainly limited by the available field for magnetizing the samples besides mechanical and thermal limitations.

The first practical prototype of a bulk HTS staggered array undulator was reported by Kinjo *et al* in 2013 [17] showing a field B_0 of 0.85 T in a 2 T solenoid for a periodicity of 10 mm and a 4 mm gap. By numerical and analytical methods, theoretically possible B_0 fields of up to 7 T were predicted for a critical current density J_c of the HTS bulk of 20 kA cm^{-2} [18]. Also Chen *et al* considered and worked on that concept [19, 20]. This design was also taken on by the Insertion Devices group at the PSI in Villigen, Switzerland, and in 2020 a bulk HTS staggered array undulator of similar performance was demonstrated, while even higher fields were predicted for the same bulks using larger magnetizing fields, see also [21].

Indeed, this collaborative work culminated recently in the record field B_0 of 2.1 T for a periodicity of 10 mm and a 4 mm gap [22], achieved with commercial GdBCO bulk samples. This value is exceeding the 2 T target value for a certain HTS undulator planned for the Swiss Light Source 2.0. By improvements in the undulator design, the machining and assembling techniques, Zhang *et al* addressed previous quench issues successfully. Shrink-fitting the HTS bulks into the copper forms improved the mechanical stability by reducing the peak stress by nearly a factor 4. This was supported by 3D electromagnetic mechanical coupled finite-element simulations and detailed measurements of the strain in bulk and copper. The field profiles, measured for different magnetization fields with a novel $x3yz$ Hall probe assembly, showed a standard deviation of ~3%. Indeed, a challenge, addressed early on [20, 23], in using HTS bulks for high-performance, i.e. highly homogeneous undulators, is the natural variation in strength and homogeneity of pinning properties and hence J_c of these HTS bulks. An important step for possible fine-tuning the individual bulk pieces has been taken by Kinjo *et al* in the same collaboration with PSI and Cambridge by developing a method for inverse analysis of the individual bulk's J_c values within the undulator [24]. Even higher fields and homogeneities can therefore be expected in the future in this type of undulator. The letter also addresses the issues of stability related to flux creep, which has been minimized by sub-cooling to 7.5 K. B_0 decreases logarithmically by around 5% within a month, and its inhomogeneity increase settles with exponential trend at just 0.1% with a characteristic time of around 2 d.

An interesting question is whether stacked-tape samples instead of bulks may lead to similarly excellent results, which would further open opportunity windows for undulator development. Furthermore, what are the limits of superconducting electro-magnet undulators? Certainly, improvements can be expected there as well.

So, are these record-field undulators superconducting or permanent-magnet undulators? Well, both actually—SCPMUs [11]—, possibly combining the best of two worlds. The letter by Zhang *et al* [22] demonstrates nicely the application potential of HTS bulks as well as the bright future of undulators in storage rings and free-electron lasers.

Data availability statement

No new data were created or analysed in this study.

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