OPTIMAL FIELD PROFILE IN LONGITUDINAL-GRADIENT SUPERBEND MAGNETS FOR THE HEFEI ADVANCED LIGHT SOURCE VIA MULTI-OBJECTIVE OPTIMIZATION

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Abstract

The Hefei Advanced Light Source (HALF) covers the VUV to soft X-ray range and plans to replace two conventional 0.9 T B4 dipoles in the storage ring with 6 T superbends to extend the photon-energy reach. Increasing the peak field while keeping the field integral unchanged leads to significant changes in the field profile, which may affect the storage-ring optics and beam parameters. To identify a field profile that preserves machine performance, this work applies a multi-objective genetic algorithm to optimize the longitudinal field distribution of the superbend. The resulting profile reduces the impact of the enhanced peak field on lattice performance and provides guidance for the magnetic design and implementation of the superbend for HALF.

INTRODUCTION

The Hefei Advanced Light Source (HALF) is designed to provide high-brightness synchrotron radiation in the vacuum ultraviolet (VUV) to soft X-ray range. To extend its photon-energy reach, the conventional 0.9 T B4 dipoles in the 5th and 15th cells are planned to be replaced by 6 T superbends, as illustrated in Fig. 1 [1].

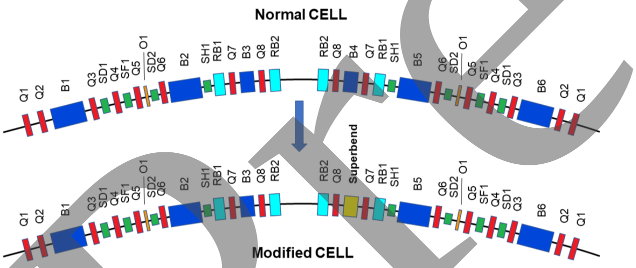

Figure 1: Magnet layout of a normal and modified cell. The LGB and superbend magnets are shown in blue and yellow, respectively.

To preserve the original bending angle, the superbend field integral should remain consistent with that of the conventional B4 dipole. With the peak field increased from 0.9 T to 6 T, the longitudinal field profile must be optimized to enhance the high-energy photon capability while maintaining acceptable lattice performance.

In this work, a multi-objective genetic algorithm is used to optimize the longitudinal field profile of the HALF superbend and provide a target profile for subsequent magnetic design.

SUPERBEND FIELD PROFILE AND OPTIMIZATION PROBLEM

Baseline Dipole and Superbend Requirement

The main B4 dipole parameters and superbend requirements are summarized in Table 1. Fig. 2 compares the B4 field profile with an illustrative superbend profile having the same field integral. Under the fixed field-integral constraint, the 6 T peak field requires a shorter effective high-field region, making the longitudinal field profile a key design variable.

Table 1: Main Parameters of the B4 Didpole and Superbend

Item	**Unit**	**B4**	**SB**
Peak field	T	0.9	6
Field integral	T·m	0.3682	
Bending angle	°	2.87	
Magnetic length	mm	560	< 500
Pole gap	mm	46	> 40
GFR	mm	±8	
$\Delta B/B$ and multipoles	/	$< 5 \times 10^{-4}$	

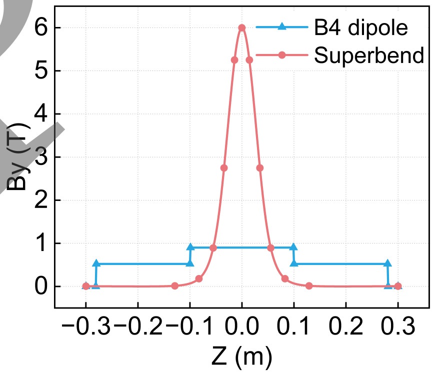

Figure 2: Longitudinal field profiles of the conventional B4 dipole and an illustrative superbend.

Field-Profile Parameterization

Previous studies have shown that hyperbolic profiles can closely approximate optimized longitudinal-gradient bending-magnet fields while maintaining a smooth analytical form [2]. Therefore, a hyperbolic-like function is adopted to parameterize the longitudinal field profile of the superbend.

Assuming symmetry with respect to the magnet center, a relative field distribution is defined as

$$B_{\mathrm{rel}}(z) = \frac{1}{\left[1 + h\left(\frac{|z|}{z_0}\right)\right]^{m}}, \qquad (1)$$

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where $z = 0$ corresponds to the magnet center, z_0 is the characteristic half length, and h and m are shape parameters.

In the lattice model, the superbend is divided into short dipole slices. The central slice is fixed at $B_p = 6\,\mathrm{T}$, and the remaining slice fields are normalized according to $B_{\mathrm{rel}}(z)$ to preserve the field integral I_0:

$$B_y(z) = \frac{I_0 - B_p \Delta z}{2\Delta z \sum_{\mathrm{half}} B_{\mathrm{rel}}(z)} B_{\mathrm{rel}}(z), \tag{2}$$

where Δz is the slice length, and the summation is taken over one half of the superbend excluding the central slice.

By varying h and m, different candidate field profiles can be generated for optimization.

MULTI-OBJECTIVE OPTIMIZATION AND LATTICE REMATCHING

A multi-objective genetic algorithm is used to optimize the superbend field profile together with local lattice rematching [3]. The overall optimization procedure is shown in Fig. 3. The optimization variables include the field-shape parameters h and m, as well as the quadrupole strengths in the half cell containing the superbend, which are allowed to vary within a limited range around their nominal values.

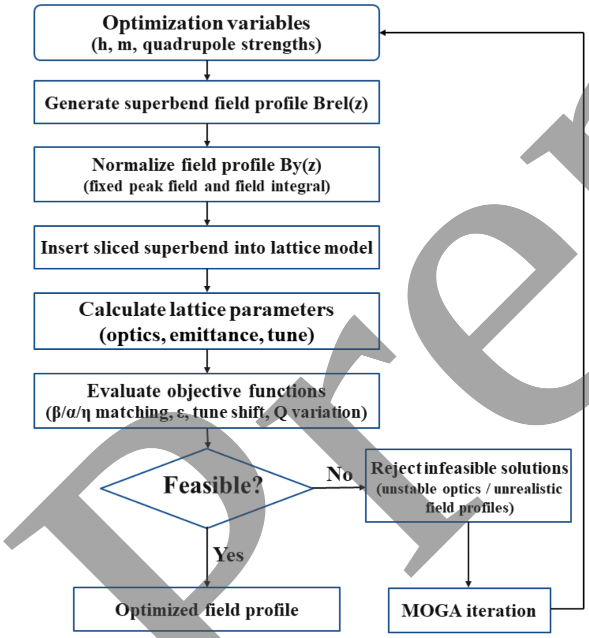

Figure 3: Flowchart of the multi-objective optimization and lattice rematching procedure.

For each candidate solution, the superbend field profile is generated, normalized to the field integral of the original B4 dipole, and introduced into the lattice model. The objective functions evaluate the matching of the β-functions, α-functions, and dispersion, as well as the natural emittance, tune shift, and quadrupole-strength variation. Solutions with unstable optics or unrealistic field profiles are excluded.

The optimization therefore identifies field profiles that satisfy the magnetic constraints while minimizing the perturbation to the rematched lattice.

OPTIMIZATION RESULTS AND DISCUSSION

After the optimization, a set of Pareto-optimal solutions was obtained. Two representative Pareto-front projections are shown in Fig. 4, illustrating the trade-offs among optics matching, emittance, tune shift, and quadrupole-strength variation. A representative compromise solution was then selected from the Pareto-optimal set.

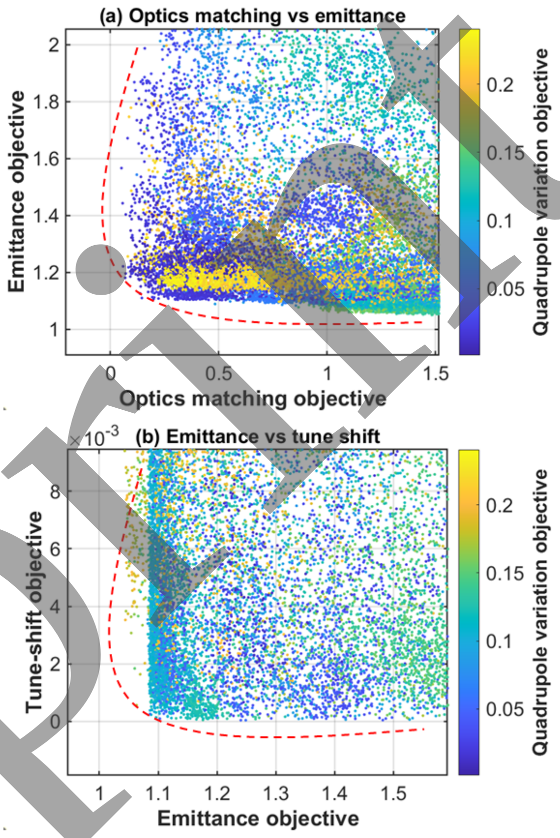

Figure 4: Two-dimensional Pareto-front projections of the multi-objective optimization results: (a) optics-matching objective versus emittance objective, with quadrupole variation indicated by color; (b) emittance objective versus tune-shift objective, with quadrupole variation indicated by color.

Fig. 5(a) shows the optimized longitudinal field profile, represented by short dipole slices in the lattice model. Fig. 5(b) compares the conventional B4 dipole and the optimized superbend profiles. The optimized profile reaches the required peak field of 6 T while preserving the field integral of the original B4 dipole.

The optical functions and magnetic-field distribution of the rematched lattice are shown in Fig. 6. After local quadrupole rematching, the β-functions and horizontal dispersion are recovered close to the baseline lattice, indicating that the perturbation introduced by the superbend can be effectively corrected.

The main lattice and beam parameters of the baseline [4] and rematched superbend lattices are summarized in Table 2. The tunes and momentum compaction factor are preserved, while the emittance, energy spread, and energy loss show

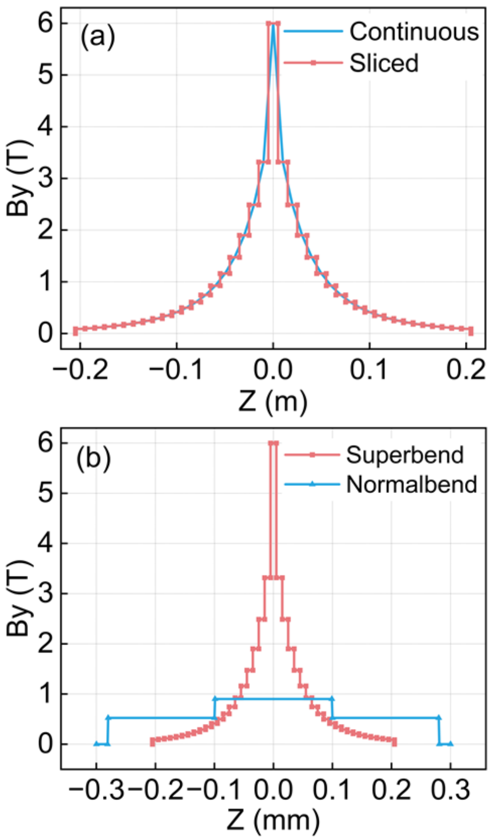

Figure 5: Longitudinal field profiles of the optimized superbend. (a) Sliced field profile used in the lattice model. (b) Comparison between the conventional B4 dipole and the optimized superbend.

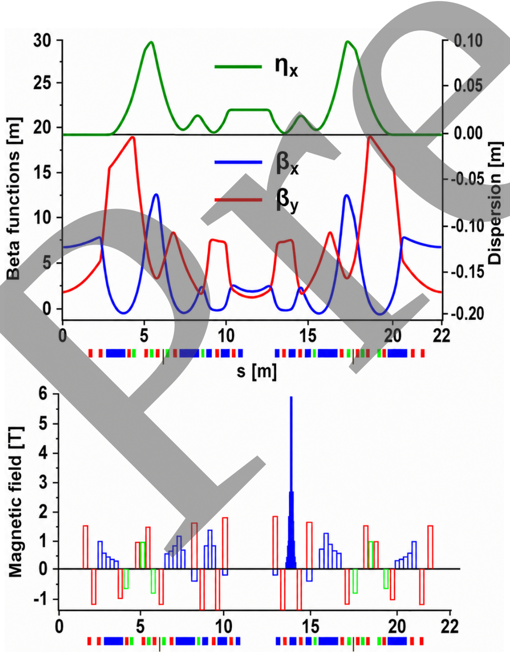

Figure 6: Optical functions and magnetic-field distribution of the rematched lattice with the optimized superbend.

moderate increases due to the enhanced radiation in the superbend. These results indicate that the optimized field profile can be accommodated in the HALF lattice and can serve as a target for subsequent magnetic design.

Table 2: Main Lattice and Beam Parameters of the Baseline and Rematched Superbend Lattices

Parameter	**Baseline**	**SB rematched**
Natural chrom. (H/V)	−81.55/ − 56.61	−81.53/ − 56.62
Emittance (pm rad)	86	89
Tunes (H/V)	48.1908/17.1895	48.1908/17.1895
RMS energy spread	6.07×10^{-4}	6.89×10^{-4}
Energy loss/turn (keV)	181.4	189.2
Mom. compact. factor	9.4×10^{-5}	9.4×10^{-5}

CONCLUSION

A longitudinal field-profile optimization study was performed for the 6 T superbend planned for the HALF storage ring. The field profile was parameterized using a hyperbolic-like function and optimized together with local quadrupole rematching by a multi-objective genetic algorithm. The optimized profile reaches the required 6 T peak field while preserving the field integral of the original B4 dipole. After rematching, the optical functions and main beam parameters remain close to the baseline values, indicating that the optimized superbend profile can be accommodated in the HALF lattice. This profile will serve as the target for subsequent magnetic design and beam-dynamics studies.

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