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Double Bend Achromat Arc Optics for 12 GeV CEBAF

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Abstract

Alternative beam optics is proposed for the higher arcs to limit emittance dilution due to quantum excitations. The new optics is implemented within the present physical layout of the arcs (baseline design); it only involves changes in quad values. The effect of synchrotron radiation is suppressed through careful lattice re-design; by appropriately organizing the Twiss functions and their derivatives inside the bending magnets. Two styles of low dispersion's emittance optics were examined: the Double Bend Achromat (DBA) and the Triple Bend Achromat (TBA). The TBA based arc design excels in minimizing the dispersion's emittance while lacking tunablity. The DBA optics still provides significantly suppressed emittance dilution, while offering superior lattice tunability and compactness. Therefore the DBA cell variety with a triplet rather then a singlet being the dispersion suppressant was chosen as a 'building block' for the arc optics. The lattices for Arcs 6 -10 were re-designed based on the above DBA structure. The resulting emittance growth was suppressed by factor of 0.64 compare to the 'Standard' Arc 6-10 optics. Finally, a 'Green Field' DBA lattice configured around individual dipole magnets was designed for Arc 10. It involved addition of 32 quads to Arc 10, which resulted in emittance growth suppression by factor of 0.5 (compare to the 'Standard' Arc 6-10 optics).

1. Dispersion's Emittance ‹H›

For 12 GeV CEBAF the synchrotron radiation effects on beam motion become rather significant in the higher arcs (energies above 6 GeV). Emissions of individual photons excite spurious betatron oscillations; the resulting energy 'drop' perturbs the electron trajectory causing its amplitudes to grow leading to cumulative emittance increase. Details of the single particle dynamics were given by M. Sands [1]; here are some major results.

The increase of beam emittance due to quantum excitations in the isomagnetic guide field of bend radius, ρ, is governed by the following expression

$$\Delta\varepsilon_x = \frac{C_q \left\langle H \right\rangle_{mag} \gamma^2}{\rho},$$

where

$$H(s) = \frac{1}{\beta(s)}\left\{ D^2(s) + \left[\beta(s) D^{'}(s) + \alpha(s) D(s) \right]^2 \right\} \qquad (1)$$

is the so called lattice invariant or dispersion's emittance and the following integral over all bending magnets is involved:

$$\langle ... \rangle_{mag} = \frac{1}{2\pi\rho} \int_{mag} ds...$$

Here,

$C_q = 3.84 \times 10^{-13} [m]$ is the so called quantum constant.

The emittance dilution is therefore determined by the energy, bending field and the Twiss functions. The last dependence in Eq. (1) will be explored to optimize higher arc optics for 12 GeV CEBAF.

2. Small ‹H› Lattices: DBA and TBA

Through careful lattice design one can appropriately 'organize' Twiss functions and their derivatives in the bending magnets, so that the value of $\langle H \rangle_{mag}$ is minimized. Two well known examples of low-‹H›, achromatic lattices: the DBA and TBA cells are illustrated in Figure 1. As one can see, for DBA lattice the strength of the middle quad is set so that the dispersion generated by the first dipole is cancelled by passing through the second one making the cell achromatic. Similar principle applies to TBA lattice where the two middle quads suppress the dispersion generated by the three dipoles.

By solving for Twiss functions inside the bend, the H-function can be expressed analytically for simple achromatic lattices, e.g. DBA and TBA [2]. Then the emittance increase can be written in the following compact form:

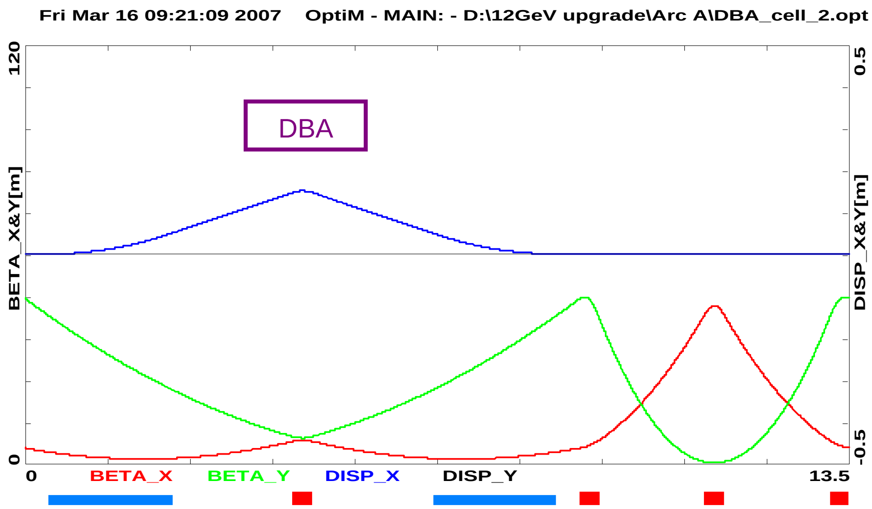
$$\Delta\varepsilon_x = C_q \; k \; \phi^3 \gamma^2 \;,$$

where

$$\phi = \frac{L}{\rho} \qquad (2)$$

is a single dipole bend angle in radians and the numerical k-factor depend only on the type of lattice structure. The corresponding k-factors for the DBA and TBA lattices are summarized below [2]:

$$k_{DBA} = \frac{1}{4\sqrt{15}} \qquad k_{TBA} = \frac{7}{36\sqrt{15}}$$



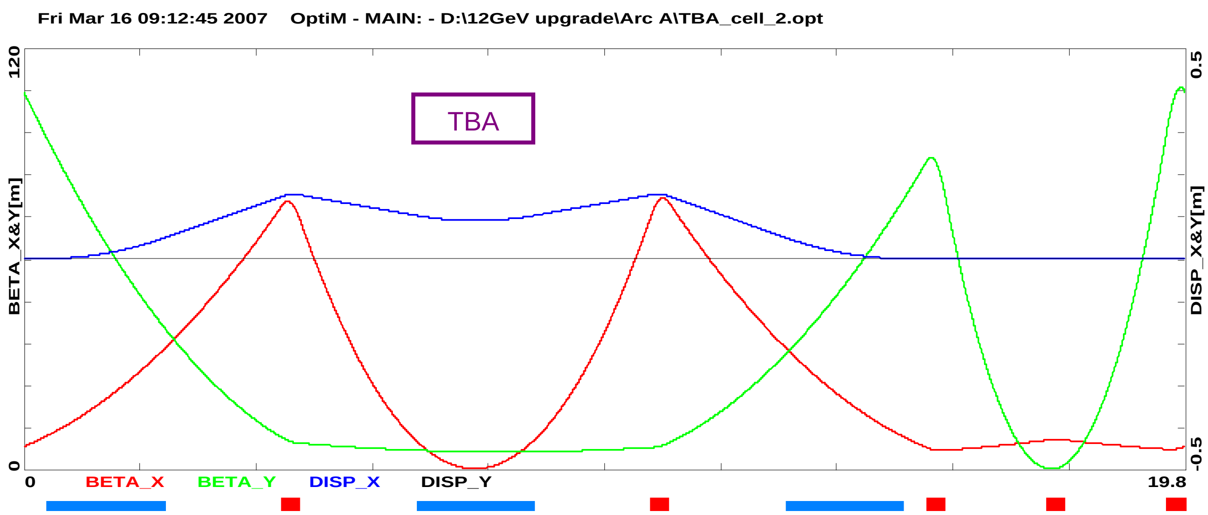
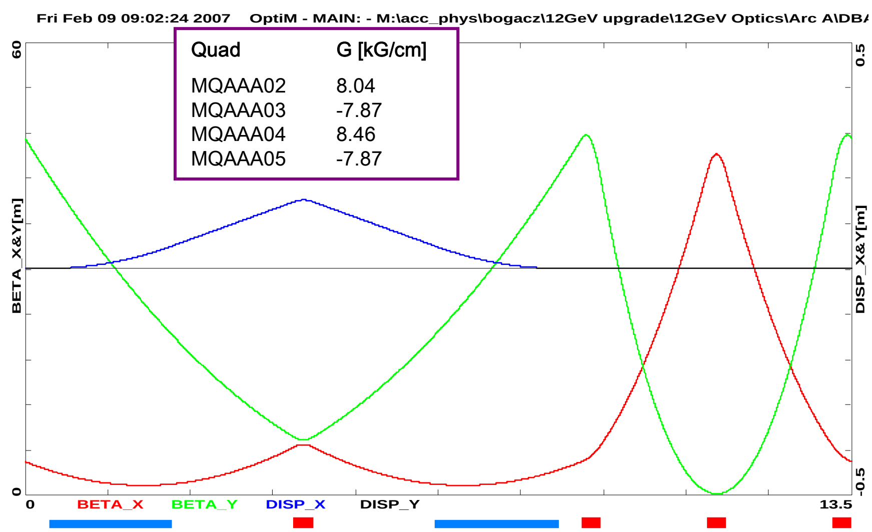


Figure 1 Low-<H> lattices: DBA and TBA periodic cells based on the same bend magnet

Although the TBA lattice excels in minimizing the dispersion's emittance (factor of 7/9 smaller then the DBA), however it lacks lattice tunability. The last 'feature' does not make it a useful building block for the arc. On the other hand, the DBA optics still offers significantly suppressed emittance dilution, while providing adequate lattice tunability and compactness. Therefore the DBA lattice is chosen.

3. DBA Cells – Design Choices

As one can see from Figure 1 the DBA cell involves: two bends, a dispersion suppression singlet between the bends and a triplet to close the cell periodically and to adjust the tunes. One may consider another variation on the DBA structure by transposing the functionality of the singlet and the triplet (now the triplet being the dispersion suppressant). The tune control is now divided between the triplet and the singlet. Both varieties of the DBA cells are illustrated in Figure 2.



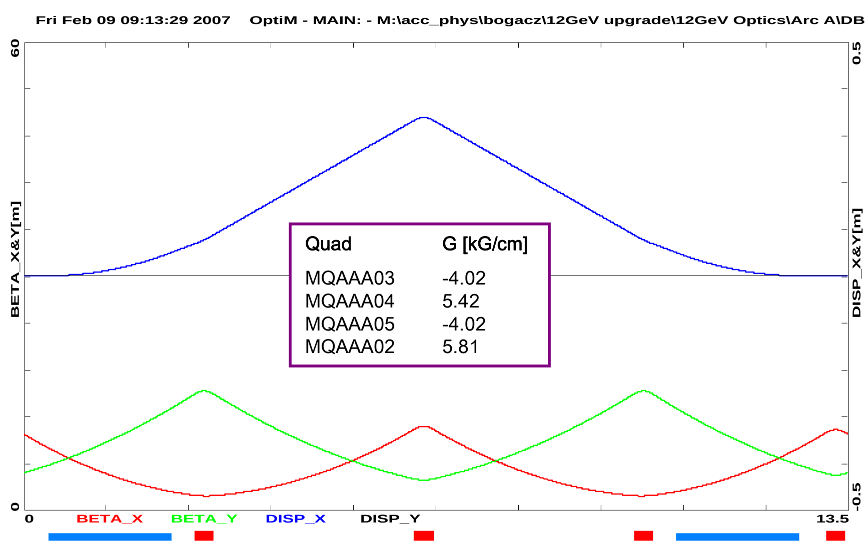
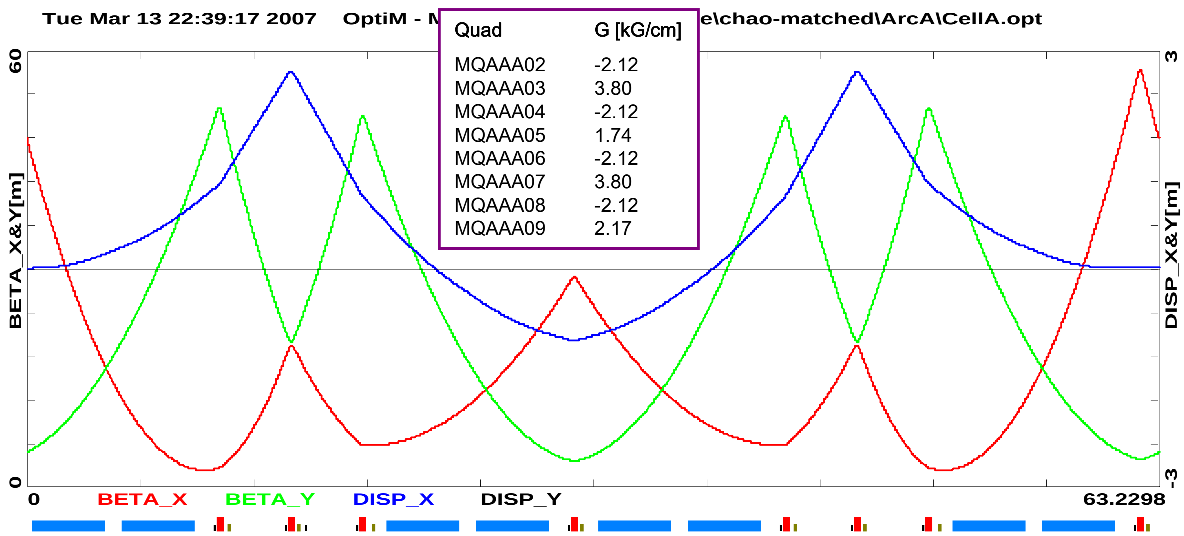


Figure 2 Two varieties of the DBA cells: dispersion suppressed via a singlet (top) and via a triplet (bottom); along with the required quad gradients at 12GeV.

One can see from Figure 2, the second style of the DBA optics (bottom plot) requires about 40% weaker quads for the same betatron tunes (Q_x = 5/8, Q_y = 3/8). Furthermore, the beta functions are factor of 3 smaller compare to the first style of the DBA optics (top plot). Another attractive feature of that optics is the ‘FODO like’ separation of the horizontal and vertical betas making the lattice well balanced and easily tunable. Therefore, the second style of the DBA optics (dispersion suppressed by a triplet) is chosen.

4. Arc Lattice Architecture – 'DBA re-tune'

The present (baseline) optics of the higher arcs is built out of 4 isochronous, achromatic periods. Figure 3 illustrates such period for Arc 10.



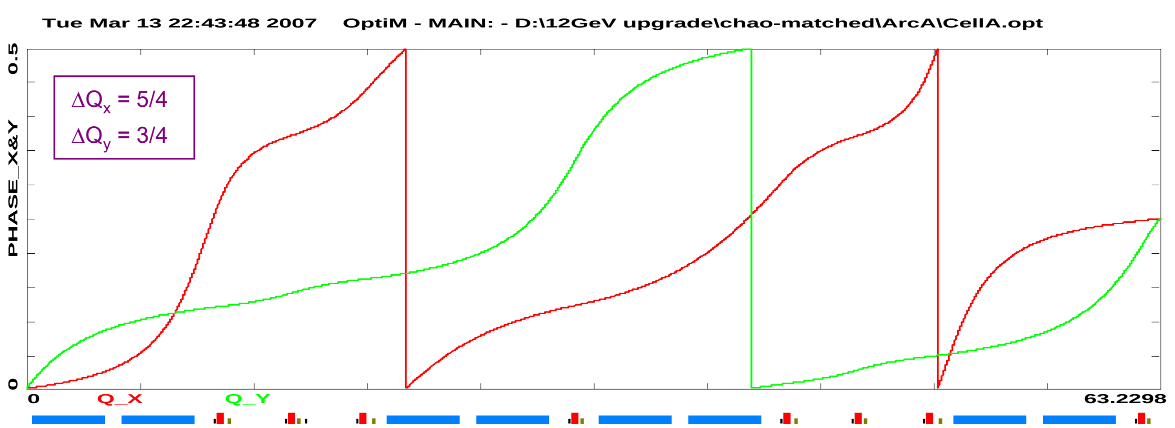
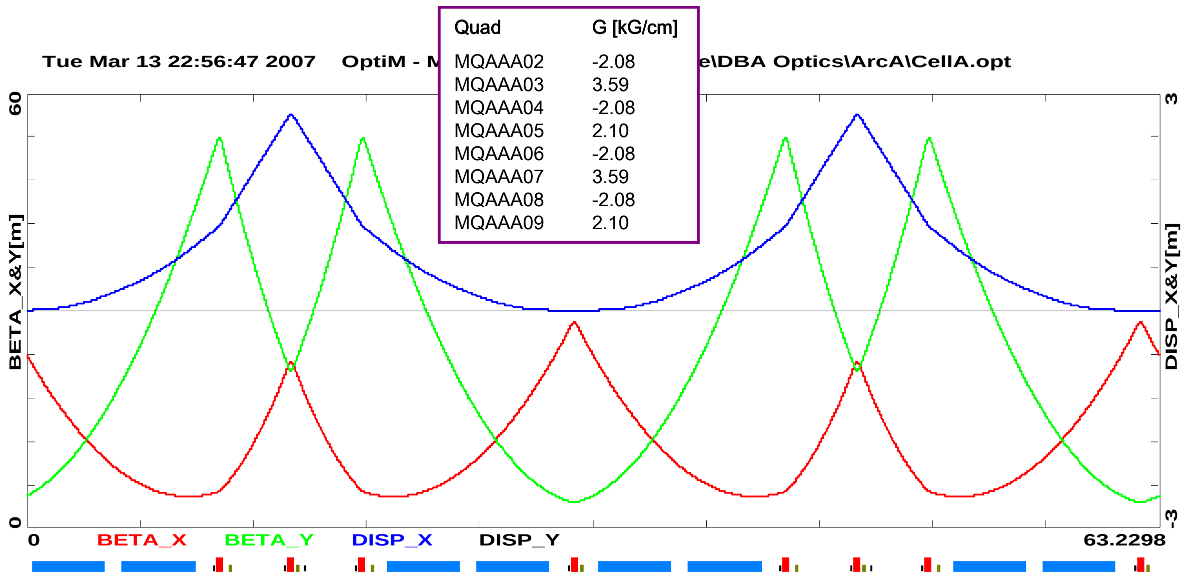


Figure 3 'Standard' optics – isochronous achromatic period of Arc 10 (Q_x = 5/4, Q_y = 3/4). Twiss functions (top), betatron phase advances (bottom).

The cell is configured with two identical triplets (providing symmetry for the achromatic closure) and two independent singlets (A05 and A09): total of 4 free parameters; allowing us to fix both tunes, to zero M_{56} and to zero the dispersion for the achromatic cell (dispersion's derivative is guaranteed to be zero by the imposed symmetry of the two triplets). However, the baseline cell ends up with rather large value of ‹H›.

To minimize the dispersion's emittance, ‹H›, one can re-tune the baseline cell (by changing the quad settings only) to split the cell in Figure 3 into two identical DBA cells formed around two pairs of bending magnets; with the triplet being the dispersion suppressant and the tune control divided between the triplet and the singlet, which is our 'preferred DBA cell' described in Figure 2 (bottom plot).



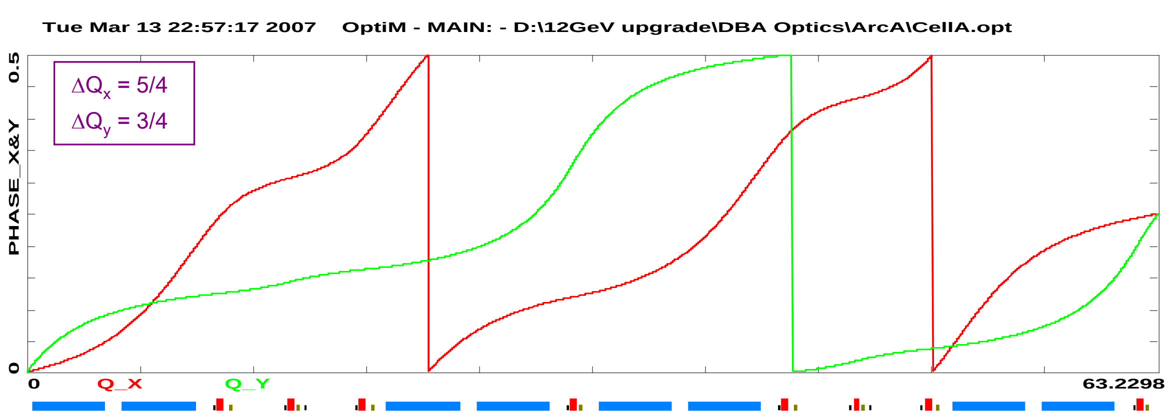


Figure 4 'DBA optics' – two identical DBA cells form a non-isochronous achromatic period in Arc 10 (Q_x = 5/4, Q_y = 3/4). Twiss functions (top), betatron phase advance (bottom).

The resulting pair of DBA cells, illustrated in Figure 4, is not isochronous; the isochronicity was purposly compromized to minimize ‹H›. Further quantitative discussion of non-zero M_{56} and its impact on the arc-linac beam dynamics will be carried out for specific Arc 6-10 lattices. Figure 5 shows comparison of the H-function for both the ‘Standard’ and the ‘DBA re-tune’ optics.

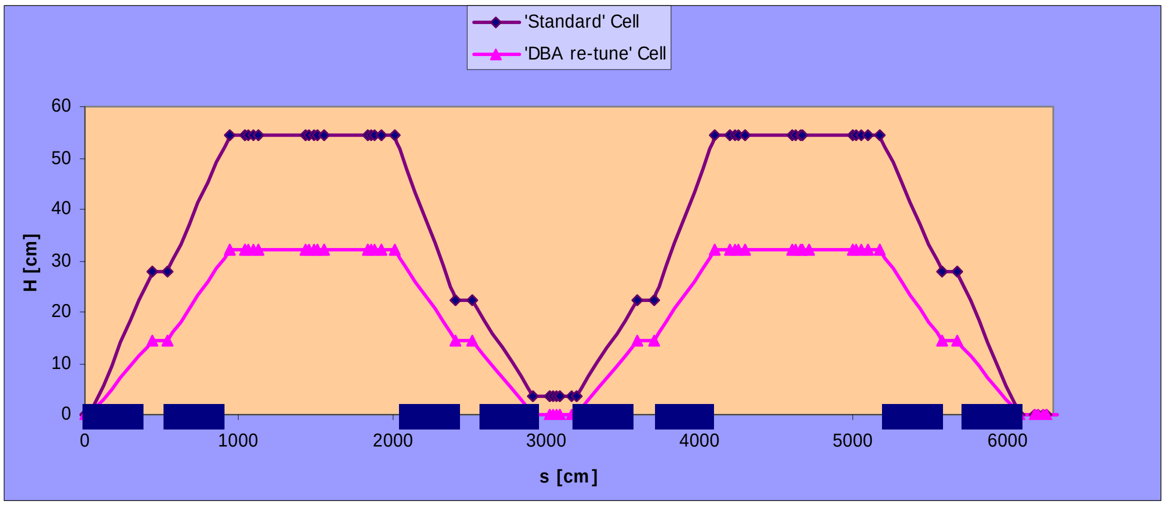


Figure 5 ‘Standard’ vs ‘DBA re-tune’ optics – the H-function is plotted across both cells (as in Figures 3 and 4. The bends are represented as ‘dark blue’ boxes on the bottom of the plot.

5. ‘DBA-retune’ Lattices for Arcs 6-10

Applying the principle of DBA re-tune described in the previous section, the new optics for Arc 6-10 was developed. Each ‘arc proper’ is now built out of 8 periodic DBA cells as illustrated in Figure 5. Then the Spreader and Recombiner quads are altered to match to the new Twiss functions of the ‘arc proper’.

Arc-by-arc comparison of both the ‘standard’ and ‘DBA re-tuned’ optics is illustrated in Figures 6-10 presented below.

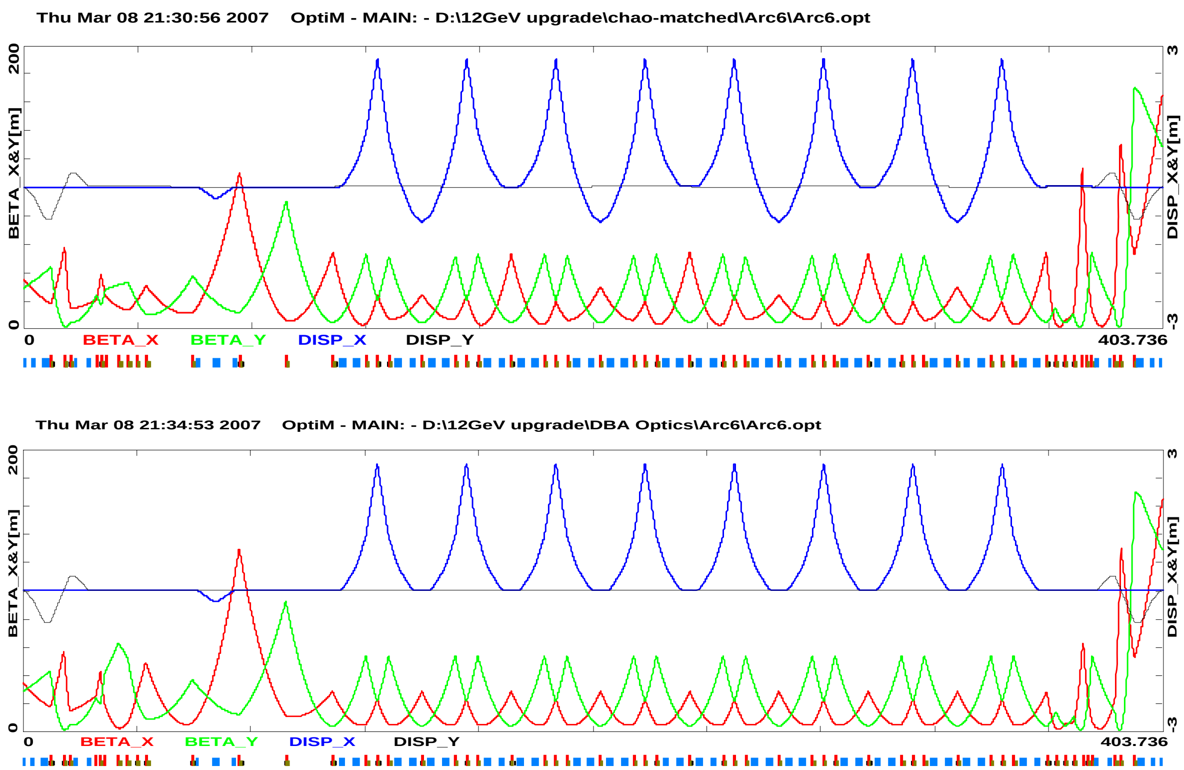


Figure 6 ‘Standard’ (top) vs. ‘DBA re-tuned’ (bottom) optics for Arc 6.

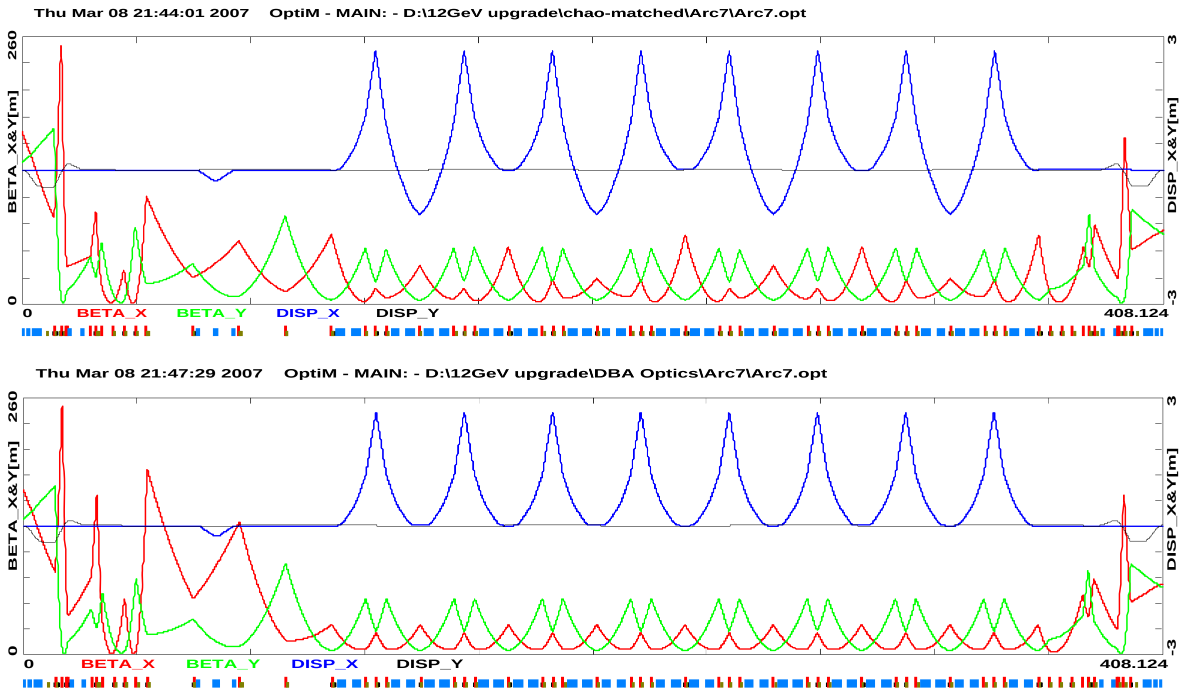


Figure 7 ‘Standard’ (top) vs. ‘DBA re-tuned’ (bottom) optics for Arc 7.

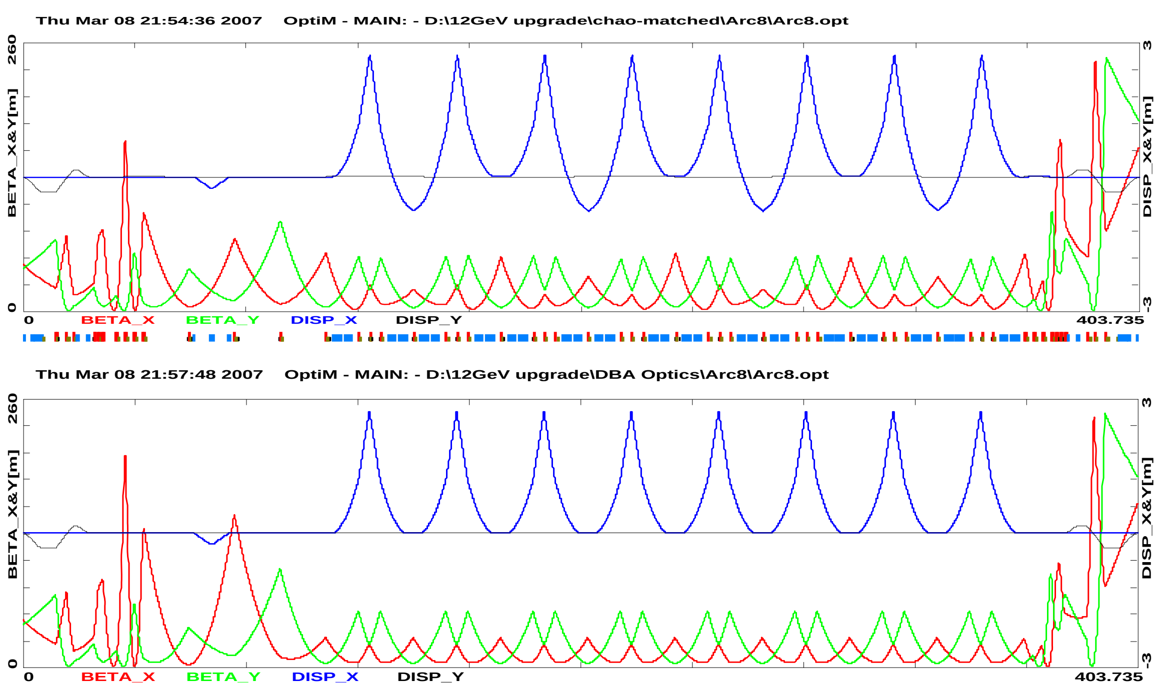


Figure 8 ‘Standard’ (top) vs. ‘DBA re-tuned’ (bottom) optics for Arc 8.

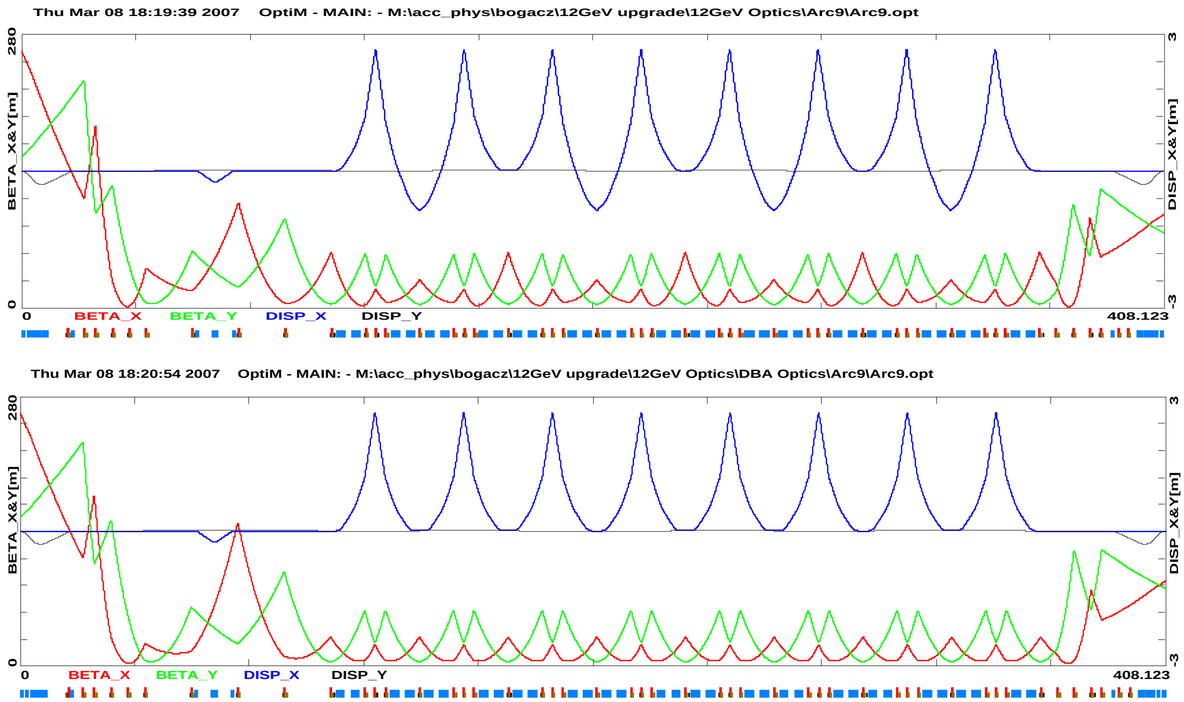


Figure 9   ‘Standard’ (top) vs. ‘DBA re-tuned’ (bottom) optics for Arc 9.

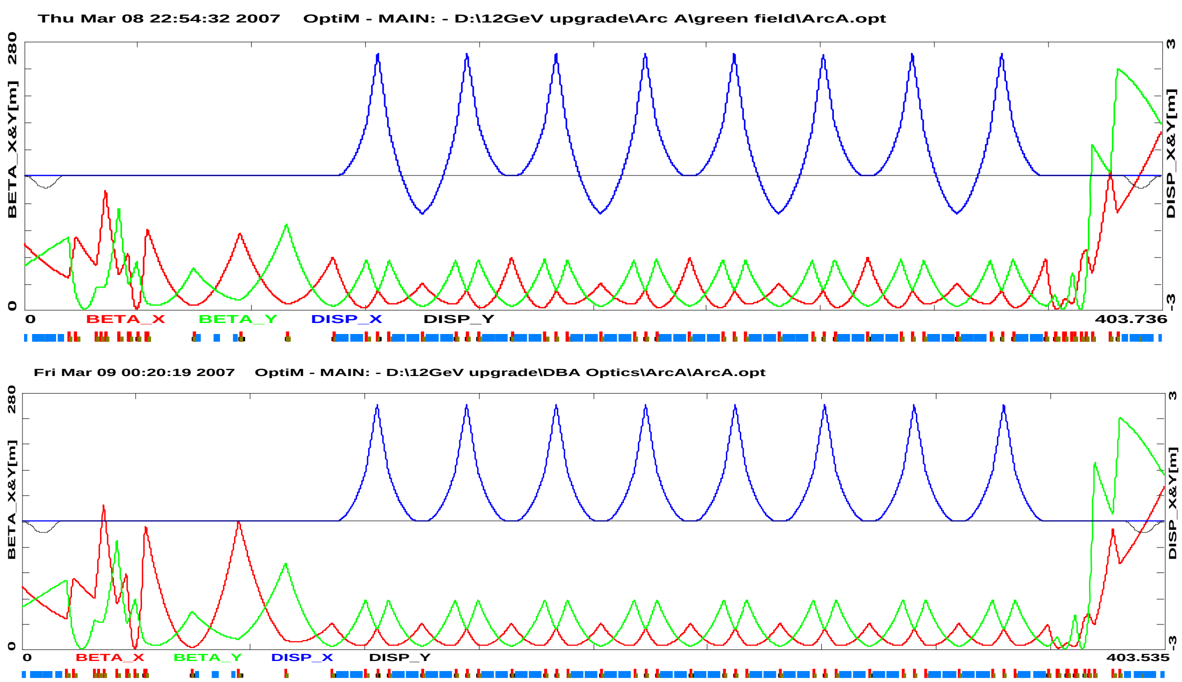


Figure 10   ‘Standard’ (top) vs. ‘DBA re-tuned’ (bottom) optics for Arc 10.

To complete the comparison of the ‘Standard’ and the ‘DBA re-tune’ optics for Arcs 6-10, one can calculate the corresponding synchrotron radiation induced emittance growth, $\Delta\varepsilon_x$, for both optics designs. The calculation of, $\Delta\varepsilon_x$, was carried out via OptiM code [3] on arc-by-arc basis using specific lattices presented in Figures 6-10. Other relevant characteristics such as: synchrotron radiation induced momentum spread and momentum compaction factor, M_{56}, were also evaluated. The results are collected in Table 1 below.

	'Standard' Optics			'DBA re-tuned' Optics			
Section	$\Delta\varepsilon_x$ [*nm rad*]	ε_x^{out} [*nm rad*]	$\frac{\Delta E}{E}\times 10^{-4}$	$\Delta\varepsilon_x$ [*nm rad*]	ε_x^{out} [*nm rad*]	M_{56} [*cm*]	$\Delta\phi_{RF}$ [deg]
Arc5		0.30	0.48		0.30		
Arc6	0.46	0.76	0.76	0.29	0.59	-70.0	0.10
Arc7	0.52	1.28	0.90	0.30	0.89	-91.2	0.15
Arc8	0.85	2.13	1.22	0.53	1.42	-69.3	0.15
Arc9	1.65	3.78	1.61	1.02	2.44	-91.3	0.26
ArcA	1.51	5.29	1.83	0.92	3.36	-92.1	0.30

Table 1 ‘Standard’ vs ‘DBA re-tune’ optics – Synchrotron radiation induced emittance growth, energy spread and M_{56}.

One can clearly see the benefit of the ‘DBA re-tune’ optics for Arcs 6-10 – suppression of the emittance growth at the end of Arc 10 by factor of 0.64.

In the ‘DBA re-tune’ optics the isochronicity was compromized to minimize ‹H›. The last two columns in Table1 show the resulting M_{56} and the corresponding phase slippage, $\Delta\phi_{RF}$

$$\Delta\phi_{RF} = -M_{56}\frac{\Delta E}{E}\,\frac{360}{\lambda_{RF}}, \tag{3}$$

(in RF degrees) at the beginning of the following linacs. The slippage of 0.3 deg. can easily be compensated by running the linacs slightly off crest. In fact, it provides additional opportunity for the longitudinal bunch compression (non-zero M_{56} combined with the appropriate gang phase in the linac will compress the bunch longitudinally). In terms of the diagnostics, this could be facilitated by adding a synchrotron light monitor in each arc [4] [5].

6. 'Green Field' design of DBA Lattice for Arcs 10

If one wants to go beyond the factor of 0.64 in emittance blowup suppression promised by previously proposed DBA re-tuned optics for Arcs 6-10, a 'Green Field' design for Arc 10 or perhaps Arc 9, where the synchrotron radiation effects are the most sizable, may be in order.

Here we propose a 'Green Field' DBA design for Arc 10, based on the same (as in the baseline design) number of 4 meter dipoles. The idea is to configure the arc into 16 DBA cells built around individual 4 meter dipoles. Previous 'DBA re-tune' optics (presented in Section 5.) involves DBA cells built around two back-to-back 4 meter dipoles acting as one 8 meter long bend. The synchrotron radiation emiitance growth in DBA structure scales as a cube of the dipole bend angle (see Eq.(2)); cutting the bend angle in half will decrease the dispersion's emittance by factor of 8, practically eliminating any emittance growth.

This design will require: two dipoles and four quads (a triplet and a singlet) per each of 16 cells; it will therefore double the number of quads (increase from 32 to 64 quads) and change the overall dipole layout to accommodate the new optics. The new 'Green Field' DBA cell is illustrated in Figure 11.

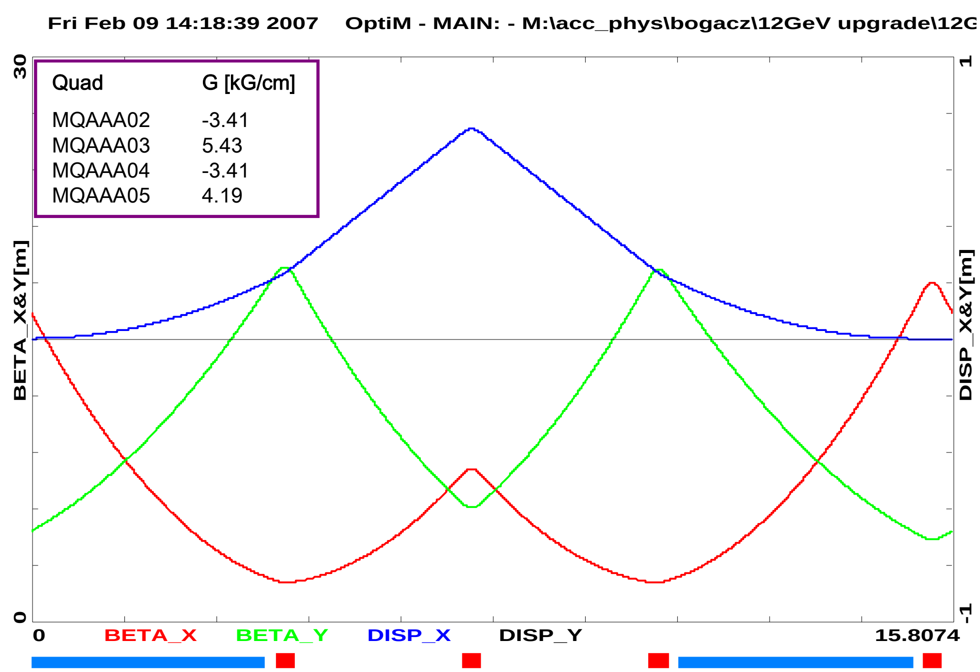


Figure 11 'Green Field' DBA optics – compact periodic cell in Arc 10; the required quad strengths are listed.

The ‘arc proper’ is now built out of 16 periodic DBA cells as illustrated in Figure 12. Again, the Spreader and Recombiner quads need to be altered to match to the new Twiss functions of the ‘arc proper’.

Comparison of both the ‘DBA re-tuned’ and the ‘Green Field’ DBA optics for Arc 10 is illustrated in Figure 12 below.

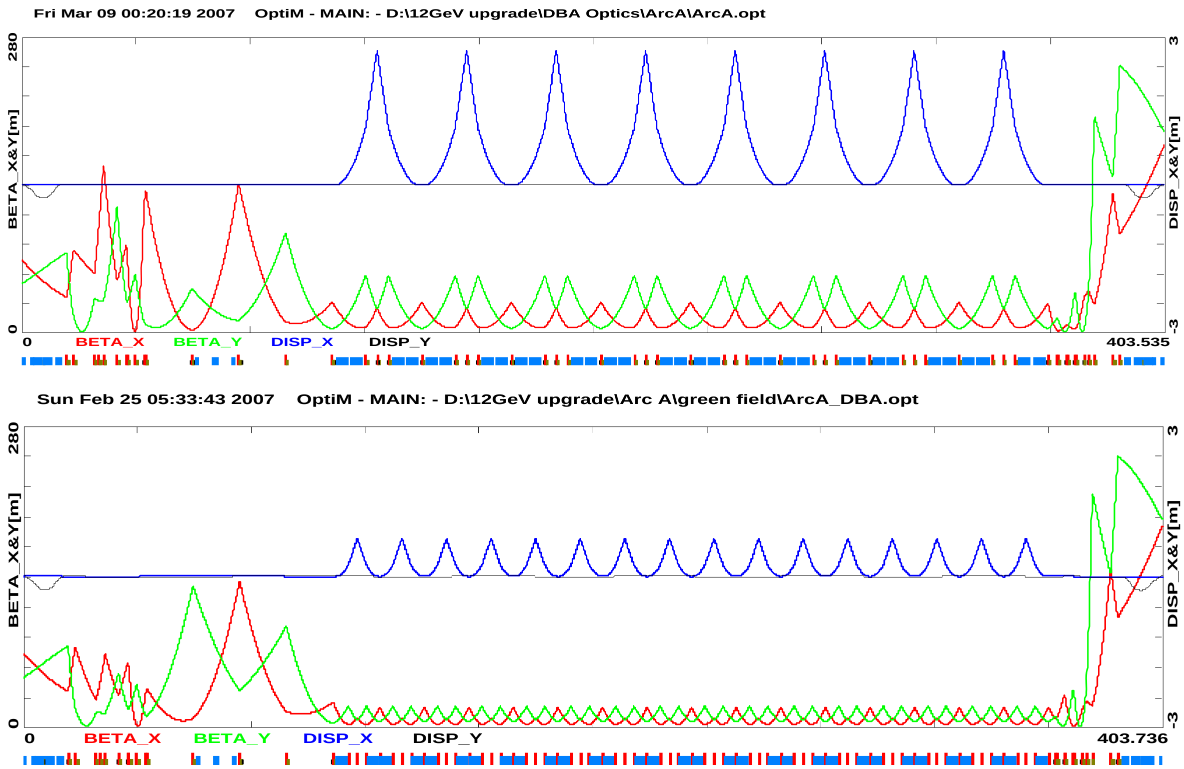


Figure 12 ‘DBA re-tuned’ (top) vs. ‘Green Field DBA’ (bottom) optics for Arc 10

To compare the ‘Standard’ optics and the ‘DBA re-tune’ optics in Arcs 6-9 plus the ‘Green Field’ DBA optics in Arc10, one can carry out similar, as in Table 1, synchrotron radiation induced emittance growth budget for both optics designs. Other relevant characteristics such as, M_{56}, were also evaluated. The results are collected in Table 2.

	'Standard' Optics			'DBA re-tuned' Optics (6-9) + 'Green Field' (10)			
Section	$\Delta\varepsilon_x$ $[nm\ rad]$	ε_x^{out} $[nm\ rad]$	$\frac{\Delta E}{E}\times 10^{-4}$	$\Delta\varepsilon_x$ $[nm\ rad]$	ε_x^{out} $[nm\ rad]$	M_{56} $[cm]$	$\Delta\phi_{RF}$ [deg]
Arc5		0.30	0.48		0.30		
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Arc9	1.65	3.78	1.61	1.02	2.44	-91.3	0.26
ArcA	1.51	5.29	1.83	0.18	2.62	-14.8	0.05

Table 2 'Standard' vs 'DBA re-tune' optics in Arcs 6-9 plus the 'Green Field' DBA optics in Arc10 – Synchrotron radiation induced emittance growth, energy spread and M_{56}.

Now the emittance growth at the end of Arc 10 is suppressed by factor of 0.5 compare to the 'Standard' optics. As seen from Figure 12 (bottom plot) the value of dispersion for tightly focused 'Green Field' DBA optics is factor of 6 smaller then for the 'Standard' one, therefore M_{56} is suppressed by the same factor of 6 resulting in negligibly small RF phase slippage of 0.05 deg.

7. Summary

Alternative beam optics is proposed for the higher arcs to limit emittance dilution due to quantum excitations. The new optics is implemented within the present physical layout of the arcs (baseline design); it only involves changes in quad values. The effect of synchrotron radiation is suppressed through careful lattice re-design; by appropriately organizing the Twiss functions and their derivatives inside the bending magnets. Two styles of low dispersion's emittance optics were examined: the Double Bend Achromat (DBA) and the Triple Bend Achromat (TBA). The TBA based arc design excels in minimizing the dispersion's emittance while lacking tunablity. The DBA optics still provides significantly suppressed emittance dilution, while offering superior lattice tunability and compactness. Therefore the DBA cell variety with a triplet rather then a singlet being the dispersion suppressant was chosen as a 'building block' for the arc optics. The lattices for Arcs 6 -10 were re-designed based on the above DBA structure. The resulting emittance growth was suppressed by factor of 0.64 compare to the 'Standard' Arc 6-10 optics. Finally, a 'Green Field' DBA lattice configured around individual dipole magnets was designed for Arc 10. It involved addition of 32 quads to Arc 10, which resulted in emittance growth suppression by factor of 0.5 (compare to the 'Standard' Arc 6-10 optics).

References

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