Jefferson Lab

Optics Restoration & Finalization Procedure

Document Number: MCC-PR-11-001

Revision Number: Rev. 13b2; **DRAFT**

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Estimated Time to Perform: 3–8 hours for all arcs

Procedure Overview

This procedure provides an overall optics check and also includes steps for restoring the beam orbit, adjusting path length, dispersion and momentum compaction factor (M_{56}), and setting the betatron functions throughout the entire accelerator. Using this procedure, you will first reproduce the orbit with maximum accuracy, then correct the pathlength in each pass through the linacs, then correct dispersion and M_{56} using specified quadrupoles in dispersive regions, and finally optimize the betatron match between arcs by adjusting specific recombiner quadrupoles.

This procedure is intended to restore and optimize either an existing "known good" optics setup (such as from an AllSave) or to establish a new baseline optics setup. As you gain experience with this procedure, you will find that some sections can be used as "tools" to solve specific optics problems without performing the entire procedure.

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This procedure is divided into sections as follows:

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Prerequisites

This procedure assumes that:

1. Beam has been threaded to the farthest downstream insertable dumplette in support of the program.
2. All RF cavities have been phased relative to the beam.
3. All quadrupoles have been cycled using HystArea.
4. All magnets are on loop and there are no relevant magnet alarms.

5. All of the following systems and applications are available to tune the accelerator:

- **FOpt** – Application used to take a snapshot of the optics for offline analysis.
- **30 Hz System** – Modulates correctors and energy for realtime tuning of the optics.
- **qtSnyder** – Application to view FOpt data and realtime 30 Hz modulation data.
- **Autosteer** – Application for optimizing the steering within an arc beamline.
- **M_{56} Cavities** – Linac RF cavities used to tune beam pathlength and M_{56}.
- **CED CMPQ** – Application to compare the setpoints for quadrupoles, dipoles, and thin septa with the design values in the CEBAF Element Database (CED).
- **Multi-Harp Emittance** – Application for aquiring harp data to determine the emittance.
- **qsUtility** – Application used to display emittance data and to compute optics.

NOTE: Always take standard FOpt data **before** making changes to **any** of the magnets of the accelerator. Take standard FOpt data as **progress** is being made and **after** the tuning has been completed. Log your results in the ELog.

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Procedure Steps

1.0 Initial Optics Check

NOTE: The following steps are intended to identify specific optics problems for an existing setup and direct you to the appropriate section of this procedure to correct the problem(s). If you are implementing a new setup and already know that the optics need to be restored and optimized, perform Steps 1–4, below, and then go directly to Section 2.0, Restoring the Orbit, on page 4 and complete the entire procedure.

1. Launch the CED-based CPMQ tool (**JTabs⇒Optics⇒CMPQ**).

   NOTE: This application calculates the design magnet settings for the energy specified on the Momentum Management System screen (**JTabs⇒Tools⇒MMS Linac Energy Set**). The calculation is based on the elegant beam physics software package, which accesses the accelerator physics model stored in the CED.

2. Check the settings for the prohibited quads in CMPQ. Are any of the magnet settings different from their design values?

   NO YES → **A.** Contact the Optics on-call person to determine if the settings are appropriate and should be left in place. Did the Optics on-call person recommend that you leave the existing values in place?

   NO: Go to Step 3

   YES NO → **B.** Return the changed quadrupoles to their design values and cycle all quads through hysteresis.

3. Send 8 μA of Tune-Mode beam and allow the orbit and energy locks to run until the absolute BPM positions converge to the lock target positions.

4. Check the Injector-to-North Linac match by inserting viewers ITV0L10, ITV0R05, ITV1L02, ITV1L06, and ITV1L10. Are all of the beam spots round (with an aspect ratio no greater than 2:1)?

YES → Go to Step 5 / NO →

   A. Open the Emittance Measurement screen (**JTabs⇒Harp⇒Multi-Harp Emittance**) and select the **Injector** tab.

   B. Insert the 0R08 insertable beam dump.

   C. Restore Tune-Mode beam current of 15 μA (required to produce clean harp traces in the following steps).

   D. Turn OFF the injector energy and orbit locks.

   E. Click on the **Scan Harps** button and wait for the data collection to be complete (scanning the harps takes several minutes).

   F. Open the Quad Scan Utility Tool (**JTabs⇒Tools⇒qsUtility**). Click on the **Collect Dataset** button. Select **Injector** and click on the relevant time-stamped data set.

   G. Click on the **Run calcEmitance** button to run the Elegant-based emittance calculation script.

   H. Click on the **configure Match Elegant** button to view the results and to calculate new quad values for the match to the 1L02 match point.

   I. Terminate beam to load the new quad values and cycle them through hysteresis.

   J. Reduce the beam current to 8 μA, turn ON the injector energy and orbit locks and allow them to run until the absolute BPM positions converge to the lock target positions.

   K. Check the Injector-to-North Linac match by inserting viewers ITV0L10, ITV0R05, ITV1L02, ITV1L06, and ITV1L10. Are all of the beam spots round (with an aspect ratio no greater than 2:1)?

   YES ↓ / NO → **L.** Contact the Optics on-call person.

   M. Go to Step 5, below.

5. Download the relative BPM positions from the STANDARD.bpm.snap file.

6. Check all relative BPM spike screens. Is the relative orbit deviation <0.5 mm in the arcs and linacs?

   YES ↓ / NO → **A.** Go to Section 2.0, Restoring the Orbit, on page 4 and perform the remainder of this procedure, starting at the point where the orbit deviation is detected.

7. Measure the path length (for detailed path length measurement information, refer to the Path Length Measurement and Correction Procedure).

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8. Compare the path length for Pass #1 to each subsequent pass. Is the difference between Pass #1 and the higher passes ≤0.5° (i.e., Pass #1 vs. Pass #2, Pass #1 vs. Pass #3, etc.)?

YES NO **A.** Go to Step 10 on page 6 of Section 2.0, Restoring the Orbit, and perform the remainder of this procedure.

9. Run a standard FOpt (**JTabs⇒Optics⇒FOpt**) to gather optics data.
10. Open the qtSnyder tool (**JTabs⇒Optics⇒Courant Snyder**) to view the results of the relevant FOpt data set.
11. Select the **Cplx** and **Cply** tabs to view the X-Y coupling data. The X-Y coupling is okay if the motion in the "unexcited" plane is less than 1/3 of that seen in the "excited" plane. Is the X-Y coupling okay?

YES NO **A.** Go to Step 2 in Section 3.0, Checking & Correcting X-Y Coupling, on page 6 and correct the X-Y coupling.

12. Select the **Disp** tab to view the dispersion data. Is the dispersion pattern nominal; i.e., are the horizontal spikes in the linacs, spreaders, and recombiners <±0.3 mm from zero (the arcs will show more dispersion, that's okay), AND are the vertical spikes within the linacs and arcs <±0.3 mm from zero (for an example, refer to Appendix D – Nominal Dispersion Patterns on page 16)?

YES NO **A.** Correct the dispersion by going to Section 5.0, Correcting Vertical Dispersion, on page 8 and performing the remainder of this procedure.

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13. Select the **CSx** and **CSy** tabs to view the Courant Snyder data. The optics match is considered acceptable if the Courant Snyder invariant varies less than ±50% across all arcs when compared to the nominal center line of Arc 1. For an example of a plot, refer to Appendix F – 30 Hz Normalized Amplitude Example on page 17. Are the normalized amplitudes stable (i.e., not growing or decaying) for all arcs?

NOTE: On occasion, some BPMs may be miscalibrated or inoperable, causing large spikes on the main plateau of the curve. Ignore such spikes when they obviously deviate from normal function.

YES NO **A.** Correct the Betatron Match by going to Section 8.0, Correcting the Betatron Match, on page 11 and perform the remainder of this procedure.

14. The present optics setup is acceptable. If you have made changes during the course of this procedure, perform an FOpt and log the results in the ELog. Perform an All-Save.
15. PROCEDURE COMPLETE.

2.0 Restoring the Orbit

? For additional technical detail pertaining to this section, refer to Appendix A – Orbit Lock and Correction Technical Discussion, on page 14.

1. Send 8 μA of Tune-Mode beam and allow the orbit and energy locks to run until the absolute BPM positions converge to the lock target positions.

2. Download the relative BPM positions from the STANDARD.bpm.snap file.
3. Open the relative BPM spike screen for the arc that you are setting up.
4. Is the relative orbit deviation *inside the arc* <0.5 mm?

   NOTE: On occasion, some BPMs may be miscalibrated or inoperable, causing large abnormal spikes in the middle of an otherwise flat BPM line. Ignore such spikes when they obviously deviate from normal function.

   YES → Go to Step 5 | NO →

   A. Check the magnet hysteresis loops for magnets in the arc and cycle any quadrupole or corrector that is off loop.

   B. Is the relative orbit deviation in the arc now <0.5 mm?

   YES → Go to Step 5 | NO →

   C. Use the “allowed” correctors in Table 2-1 on page 6 to manually adjust the orbit in the arc. Are the relative orbit deviations in the arc <0.5 mm?

   NOTE: The goal is to reproduce the “golden” orbit in the arc as faithfully as possible. There are no limitations as to which correctors can be used *within an arc* to correct the orbit in that arc; however, always try to first use the “allowed” correctors listed in Table 2-1 on page 6. Also, correctors acting in the focusing plane of a neighboring quadrupole are preferred; that is, horizontal correctors neighboring quadrupoles with a positive gradient and vertical correctors neighboring quadrupoles with a negative gradient.

   YES → Go to Step 5 | NO →

   D. Open the Autosteer application (**JTabs⇒Optics⇒Autosteer**) and the *Beam Energy Monitor Screen* (**JTabs⇒Tools⇒BEM**).

   E. Open the **File** menu in Autosteer and load the relevant arc segment. Autosteer the arc in both the X and Y planes. Are the relative orbit deviations in the arc now <0.5 mm?

   YES ↓ | NO →

   F. Contact the Optics on-call person.

   G. On the *Beam Energy Monitor Screen*, is the **dp/p corr** value (i.e., corrector momentum error) for the relevant arc $<5\times10^{-4}$?

   YES → Go to Step 5 | NO →

   H. Using the **dp/p corr** value and with the shunts in B-dL mode, adjust the dipole Integral B-dL for the relevant arc. Change the Integral B-dL setting by the amount of the **dp/p corr** value, observing the sign (+ or -) of the change. This shifts orbit correction from the correctors in the arc,

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into the arc dipoles (i.e., the correctors won't have to work so hard).

I. Autosteer the relevant arc. If the relative orbit deviations in the arc are now <0.5 mm, go to Step 5, below, otherwise, contact the Optics on-call person.

5. Open the relative BPM spike screen for the linac downstream from the arc that you are setting up.
6. Using the correctors shown in Table 2-1, minimize the relative orbit deviation in the recombiner, linac, and spreader.

Table 2-1: "Allowed" Correctors for Recombiner, Linac and Spreader Orbit Correction

	Arc 1	Arc 2	Arcs 3	Arc 4	Arc 5	Arc 6	Arc 7	Arc 8	Arc 9	Arc 10
"Allowed" Spreader Magnets	1A01H 1A07V	2A01H 2A07V	3A01H 3A08V	4A01H 4A08V	5A01H 5A08V	6A01H 6A08V	7A01H 7A08V	8A01H 8A08V	9A01H 9A08V	AA01H AA08V
"Allowed" Recombiner Magnets	1R06H 1R09H 1R07V 1R10V	2R06H 2R09H 2R04V 2R10V	3R06H 3R09H 3R07V 3R10V	4R06H 4R09H 4R04V 4R10V	5R06H 5R09H 5R04V 5R10V	6R06H 6R09H 6R04V 6R10V	7R06H 7R09H 7R04V 7R10V	8R06H 8R09H 8R08V 8R10V	9R03H 9R08H 9R03V 9R07V	AR06H AR09H AR06V AR08V

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7. Cycle all changed correctors (except lock correctors) through hysteresis.
8. Recheck the orbit.
9. Repeat Steps 1–8 for all downstream arcs.
10. Open the Path Length Measurement screen and measure the path length (for detailed path length measurement information, refer to the Path Length Measurement and Correction Procedure).
11. Compare the path length for Pass #1 to each subsequent pass. Is the difference between Pass #1 and the higher passes ≤0.5° (i.e., Pass #1 vs. Pass #2, Pass #1 vs. Pass #3, etc.)?

YES NO

Go to Section 3.0

A. For linacs 3L–AL, adjust the path length by changing the dogleg in the upstream arc. For linac BL, adjust the pathlength by offsetting the orbit in Arc 10. After making any corrections, go to Section 3.0, Checking & Correcting X-Y Coupling, on page 6, below.

NOTE: When a dogleg is adjusted, the orbit locks will automatically correct any orbit changes. You should, however, verify that the orbit did not change. Also, cycle the dogleg through hysteresis only if you have changed it by more than 5% of its maximum value.

3.0 Checking & Correcting X-Y Coupling

NOTE: Potential sources of X-Y coupling are skew quadrupole fields from RF cavity couplers and bad orbits in a spreader or recombiner. If you have not already checked the optics in the accelerator, go to Section 1.0, Initial Optics Check, on

page 2 and check the optics before proceeding with the following steps to correct X-Y coupling.

1. Check for X-Y coupling as follows:
   a. Open the 30 Hz Switch screen (**JTabs⇒Global Diagnostics⇒30 Hz Switch**). Press the **30 Hz** button to engage the system into 30 Hz mode at 1.5 Volts.
   b. Open the 30 Hz absolute BPM spike screens for Arc 1, Arc 2, and the highest arc that is transporting beam.
   c. Select 1E01H from the pull-down menu, and save the resulting absolute BPM screens to the ELog and label them as “1E01H”.
   d. Repeat Step c, above, for 1S08H, 1S09V, and 1E01V.
   e. Compare the X and Y traces within each of the arcs. Is the motion in the “unexcited” plane (X or Y) less than 1/3 of that seen in the “excited” plane?

   NO YES ➔ **A.** The X-Y coupling is okay, go to Step 4, below.

   f. On the 30 Hz Switch screen, select **All Systems Off** from the pull-down menu, press the **OFF** button at the top of the screen, then go to Step 2, below, to correct the X-Y coupling.
2. Correct the X-Y coupling as follows:

   Arcs 1–7:

   a. Open the Skew Quad Scaling tool (**JTabs⇒Magnets⇒Magnet Commander⇒Skew & Lock Screens⇒Skew Quads - North Linac**) and at the bottom of the screen, select **Adjust Skew**.
   b. On the Skew Quad Scaling screen, click on the **View Values** button.
   c. On the screen that opens, click on the **Scale Skews** button (this automatically begins scaling the skew quads using the default Fudge Factor value of 1.0—note that this fudge factor is not the same as the LEM fudge factor). Monitor the process by watching the message bar at the top of the screen; a message will appear when the process is complete. The **Current Skew** column will show any changes that are made.

   Arcs 8–9:

   a. While observing the Arc 8 bpms, adjust skew quad MQD8S04 in 100 G-cm steps to minimize the cross-plane amplitude in the unexcited plane.
   b. While observing the Arc 9 bpms, adjust skew quad MQD9S02 in 100 G-cm steps to minimize the cross-plane amplitude in the unexcited plane.
3. Recheck the X-Y coupling by repeating Step 1, above. Has the coupling problem been corrected?

   YES NO ➔ **A.** Iterate Step c, above, changing the Fudge Factor value in 0.01 increments (start with 1.01) and then rechecking the X-Y coupling. If changing the Fudge Factor in a positive direction makes the coupling worse, move in a negative direction (0.99, etc.). If you do not converge toward a solution, contact the Optics on-call person.

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4. On the 30 Hz Switch screen, select **All Systems Off** from the pull-down menu, and press the **OFF** button at the top of the screen.
5. Go to Section 4.0, Measuring Dispersion, on page 8.

4.0 Measuring Dispersion

1. Open the *30 Hz Switch* screen (**JTabs⇒Global Diagnostics⇒30 Hz Switch**). Press the **30 Hz** button to engage the system into 30 Hz mode at 1.5V.
2. Open the absolute 30 Hz spike screen for the arc that you are setting up.
3. Select **RF** from the pull-down menu. Adjust the Function Generator 30 Hz amplitude to provide a 5 mm differential orbit on the *Arc 1 30 Hz BPM* screen.
4. Is the dispersion pattern nominal; i.e., are the horizontal spikes in the linacs, spreaders, and recombiners <±0.3 mm from zero (the arcs will show more dispersion, that's okay), AND are the vertical spikes within the linacs and arcs <±0.3 mm from zero (for an example, refer to Appendix D – Nominal Dispersion Patterns on page 16)?

   YES ↓ NO → **A.** Correct the dispersion problems using the following sections in this procedure.

5. Go to Section 7.0, Measuring and Correcting M56, on page 10.

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5.0 Correcting Vertical Dispersion

NOTE: When changing any quadrupole settings during this procedure, IT IS IMPORTANT to maintain the existing orbit in the arc that you are setting up. Monitor the arc's relative spike screen for changes >0.2 mm in the orbit (this can be done by a second operator). Immediately correct changes in the orbit by adjusting the correctors closest to the quadrupole that caused the change.

1. Open the relative BPM screens for the arc that you are setting up and zero the BPMs' position offset (these will be used to monitor the orbit—see note above).
2. **FOR ARC 1 ONLY**:
   a. While referencing the 30 Hz spike screen for Arc 1, adjust quadrupole 1S01 to minimize vertical dispersion in Arc 1.
3. **FOR ARCS 2–8 ONLY:**

   NOTE: Before correcting the vertical dispersion in an arc (Arc *n*), first correct the vertical dispersion in all upstream arcs.

   a. While referencing the 30 Hz spike screen for the *n* Linac, adjust the (*n*-1)R10 quadrupole to minimize the dispersion leakage in the *n* Linac.

b. While referencing the 30 Hz spike screen for Arc *n*, adjust quadrupole *n*S01 (see Table 5-1) to minimize vertical dispersion in Arc *n*.

Table 5-1: Vertical Dispersion Correction Quadrupoles

	Arc 1	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6	Arc 7	Arc 8	Arc 9
***n*S01**	1S01	2S01	3S01	4S01	5S01	6S01	7S01	8S01	
(*n*–1)R10		1R10	2R10	3R10	4R10	5R10	6R10	7R10	8R10

c. Repeat the vertical dispersion correction procedure for the next downstream arc.

4. **FOR ARC 9 ONLY:**

NOTE: Before correcting the vertical dispersion in Arc 9, first correct the vertical dispersion in all upstream arcs. The Spreader for Arc 9 does not have adequate knobs to control the dispersion. Only 8R10 is available as a dispersion control knob for Linac 9 and Arc 9.

a. Adjust the setting of quadrupole 8R10 to minimize the dispersion leakage into the *n* Linac and *n* Arc.

5. Are the vertical dispersion spikes within the linacs and arcs <±0.3 mm from zero (for an example, refer to Appendix D – Nominal Dispersion Patterns on page 16)?

YES NO → **A.** Contact the Optics on-call person.

6. Go to Section 6.0, Correcting Horizontal Dispersion, on page 9.

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6.0 Correcting Horizontal Dispersion

? For additional technical detail pertaining to this section, refer to Appendix B – Horizontal Dispersion Correction Technical Discussion, on page 14.

1. On the CMPQ output generated earlier in this procedure, check the eight horizontal dispersion-determining quadrupoles listed in Table 6-1 for Arc *n* to see if the Design values match the Machine values (i.e., there are no numbers listed in the Difference column of the printout).

Table 6-1: Horizontal Dispersion-Determining Quadrupoles

Arc 1	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6	Arc 7	Arc 8	Arc 9	Arc 10
1A11	2A08	3A03	4A03	5A03	6A03	7A03	8A03	9A03	AA03
1A21	2A21	3A07	4A07	5A07	6A07	7A07	8A07	9A07	AA07
		3A11	4A11	5A11	6A11	7A11	8A11	9A11	AA11
		3A15	4A15	5A15	6A15	7A15	8A15	9A15	AA15
		3A19	4A19	5A19	6A19	7A19	8A19	9A19	AA19
		3A23	4A23	5A23	6A23	7A23	8A23	9A23	AA23
		3A27	4A27	5A27	6A27	7A27	8A27	9A27	AA27
		3A31	4A31	5A31	6A31	7A31	8A31	9A31	AA31

2. Do the Design settings match the Machine values (the design values for all eight magnets should be the same)?

YES NO → **A.** Zero the relative BPMs for the arc you are setting up (Arc *n*).

Go to Step 3

B. One at a time, change the settings for the Arc *n* quadrupoles listed in Table 6-1 back to the Design values listed in the CMPQ output.

C. Using the correctors adjacent to the changed quadrupoles, smooth out the relative BPM orbit in Arc *n*.

D. Go to Step 3, below.

3. Open the 30 Hz spike screens for the arc that you are setting up (Arc *n*) and for the next downstream arc (Arc *n*+1).
4. Referring to Table 6-2, adjust Quad 1 and Quad 2 to minimize the horizontal dispersion at the output of the arc that you are setting up and at the input of the downstream arc.

Table 6-2: Horizontal Dispersion Correction Quadrupoles

	Arc 1	Arc 2	Arcs 3–10
Quad 1	1A11	2A08	*n*A23
Quad 2	1A21	2A21	*n*A31

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5. Are the horizontal spikes in the linacs, spreaders, and recombiners <±0.3 mm from zero (the arcs will show more dispersion, that's okay) (for an example, refer to Appendix D – Nominal Dispersion Patterns on page 16)?

YES NO → **A.** Contact the Optics on-call person.

6. Open the 30 Hz Switch screen, select **All Systems Off** from the pull-down menu, and press the **OFF** button at the top of the screen.
7. Go to Section 7.0, Measuring and Correcting M56, on page 10.

7.0 Measuring and Correcting M_{56}

1. Open the *M56 Measurement Controls* screen (**JTabs⇒Optics⇒Pathlength/M56 Amp & Phase**).
2. While referencing the waveform for the linac that follows the arc, use the relevant phase slider to set the M_{56} signal to zero crossing.
3. Open the *Expert* screen and set the amplitude slider to 0.612 volts.

   NOTE: This will provide a linac cavity calibration of 150 mV/degree for the south linac OR 170 mV/degree for the north linac (as measured on the oscilloscope for the linac that follows the arc).
4. Readjust the phase slider as necessary to set the M_{56} signal for the arc to zero crossing.

   NOTE: If, for example, you are setting up Arc 4, the third hump on the north linac cavity signal should be zeroed.

5. Record an image of the M_{56} signal oscilloscope trace to ELog and label it with the present dp/p values.
6. Turn off the orbit lock in the arc that you are setting up.
7. Using the 1A and 2A energy locks, decrease the energy in both linacs to dp/p = 0.001.
8. Record an image of the M_{56} signal oscilloscope trace to the ELog and label it with the present dp/p values.
9. Compare the waveforms that were captured in Step 5 and Step 8, above. Is the difference between Pass 1 and all higher passes <75 mV (or path length within <0.5°)?

YES NO Go to Section 8.0

A. Open the M_{56} Tool (**JTabs⇒Optics⇒M_{56} Tool**). Select the relevant tab from the interface based on the arc being tuned:

- **Arc 1** – Change the BDL settings for quads 1A11 and 1A31 by +100 G-cm.
- **Arc 2** – Change the BDL settings for quads 2A08 and 2A34 by +100 G-cm.
- **Arcs 3–10** – Change the BDL settings for all eight dispersion-determining quadrupoles (refer to Table 6-1 on page 9) by +100 G-cm.

B. Repeat Steps 4–9, above. Is the difference <75 mV (or a path length differential of <0.5°)?

YES NO **C.** Repeat Steps A–B, above, repeating as necessary in both a positive and negative direction until the difference is <75 mV (or a path length differential of <0.5°).

NOTE: Based on the degree of change noted in the first 100 G-cm step, you may want to scale the next quadrupole step accordingly.

D. Go to Section 6.0, Correcting Horizontal Dispersion, on page 9 and repeat the horizontal dispersion correction procedure.

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8.0 Correcting the Betatron Match

? For additional technical detail pertaining to this section, refer to Appendix C – Betatron Match Correction Technical Discussion, on page 14.

1. Start the qtSnyder Tool (**JTabs⇒Optics⇒Courant Snyder**) to measure the normalized amplitude of the betatron motion; for additional information, refer to the 30 Hz Courant Snyder User's Guide).
2. Check the X and Y plot screens. Are the normalized amplitudes stable (i.e., not growing) for all arcs (and the corresponding Hall beam line, if applicable)? The optics match is considered acceptable if the Courant Snyder invariant varies less

than ±50% across all arcs when compared to the nominal center line of Arc 1; refer to Appendix F – 30 Hz Normalized Amplitude Example on page 17.

NOTE: On occasion, some BPMs may be miscalibrated or inoperable, causing large spikes on the main plateau of the curve. Ignore such spikes when they obviously deviate from normal function.

YES NO **A.** Skip to Step 4, below, and follow the procedure to correct the betatron match.

3. Go to Section 1.0, Initial Optics Check, on page 2 and perform a final check of the optics to verify that the accelerator setup is acceptable.
4. Open the *30 Hz Switch* screen (**JTabs⇒Global Diagnostics⇒30 Hz Switch**) and select 1S08H from the pull-down menu.
5. While observing the X (horizontal) plot screen, adjust the ***horizontal*** beta-matching quadrupoles for the arc that you are setting up (refer to Table 8-1 for the appropriate quadrupoles and see the explanation note below) until the normalized amplitudes in the arc are equal to the Arc 1 normalized amplitude (i.e., not growing).

Table 8-1: Betatron Matching Quadrupoles

	Arc 1	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6	Arc 7	Arc 8	Arc 9	Arc 10	Lin B
H		1R03 1R06	2R01 2R02	3R01 3R03	4R01 4R04	5R02 5R03	6R01 6R02	7R01 7R05	8R01 8R03	9R01 9R02	AR01 AR05
V		1R02 1R04	2R04 2R05	3R04 3R07	4R02 4R05	5R04 5R06	6R04 6R05	7R02 7R06	8R02 8R04	9R03 9R06	AR04 AR07

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6. On the *30 Hz Switch* screen, select 1E01H.
7. While observing the X (horizontal) plot screen, adjust the ***horizontal*** beta-matching quadrupoles for the arc that you are setting up until the normalized amplitudes in the arc are stable (i.e., not growing or decaying).
8. Insert the viewer in the spreader immediately downstream from the arc you are setting up. Is the beam spot elongated (aspect ratio greater than 2:1)?

NO YES **A.** Repeat Steps 4–8, above, until the beam spot is no longer elongated. If the spot shape cannot be corrected, contact the Optics on-call person.

9. Repeat Steps 4–8, above, optimizing the horizontal normalized amplitude by finding the best possible balance between quadrupoles for the excitation of both correctors, 1S08H and 1E01H, and then proceed to the next step.
10. Using 30 Hz correctors 1S09V and 1E01V, repeat Steps 4–8 to perform the ***vertical*** betatron match.
11. Repeat Steps 4–10, above, as necessary to optimize the horizontal betatron match and the vertical betatron match (the horizontal match may change slightly after the vertical match is corrected, and vice versa; repeat the matching procedures as necessary to minimize these changes).

12. On the *30 Hz Switch* screen select "**All Systems Off**" from the pull-down menu and press the **OFF** button at the top of the screen.
13. Return to Section 1.0, Initial Optics Check, on page 2 and perform a final check of the optics to verify that the accelerator setup is acceptable.

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Appendix A – Orbit Lock and Correction Technical Discussion

In order to accommodate performance of this procedure, the orbit locks have been moved to locations with greater beta functions. This was done to decrease beam displacement due to drifts and noise on the BPMs. To simplify the golden orbit values, they are zeroed in this procedure, except in even arcs where the beam has to have a +5.5 mm offset at BPM *n*E02H in order to bypass the extraction septa.

It has been determined that resteering the accelerator *significantly* degrades the dispersion and beta functions. In addition to a change in focusing, there is also a skew-quadrupole component if the beam is vertically displaced. This skew-quadrupole field causes coupling of the vertical and horizontal beam motions and "pumps up" the vertical dispersion based on the horizontal dispersion.

The horizontal dispersion is also affected by resteering in the arcs, but the effect is smaller. Thus, to reproduce good optics, it is important to reproduce the same orbit. The vertical orbit in the arcs must be reproduced with maximum accuracy.

Because the corresponding BPMs are located in places with larger beta functions, the new orbit locks are more stable in the vertical direction.

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The most important new requirement is not to create a good orbit, but to reproduce the old orbit as accurately as possible. If the orbit is reproduced, the optics will be restored and a total optics setup can be avoided.

Return to Section 2.0, Restoring the Orbit, on page 4.

Appendix B – Horizontal Dispersion Correction Technical Discussion

The goal of the horizontal dispersion correction procedure is to have zero dispersion on the output of the arc and, at the same time, correct (equalize) the periodic spikes inside the arc (remember that there are four superperiods that are identical with regard to dispersion). If you successfully correct the spike behavior, you will not need to adjust M_{56}.

Return to Section 6.0, Correcting Horizontal Dispersion, on page 9.

Appendix C – Betatron Match Correction Technical Discussion

The goal of the betatron match procedure is to correct the betatron functions and get correct beam envelopes through the entire accelerator. To accomplish this, we excite betatron oscillations at the beginning of Arc 1 and then watch how the amplitude of this modulation changes with beam propagation throughout the entire accelerator. As theory states, this amplitude must decrease with beam acceleration inversely proportional to the square root of energy. Thus, an initial amplitude of 3 mm in Arc 1 should decrease to approximately 1 mm in Arc 10. Although this works in theory, in practice it is impossible to extract the betatron amplitude from the spike amplitudes. To solve this problem, a software program was created to calculate the normalized amplitude of the motion for each BPM so that this amplitude remains constant if the lattice coincides with the design lattice. The amplitude is changed by elements that have parameters that are different from the design and it (the amplitude) can be increased or decreased depending on the betatron phase.

To excite the beam, four air-core correctors located in the 1S–1E region are used. These correctors excite transverse beam oscillations that have a frequency of 30 Hz and different betatron phases so that the system will be sensitive to errors from all quadrupoles. Two of these four air-core correctors are horizontal and two are vertical. Each pair of correctors (horizontal and vertical) has a betatron phase advance of approximately 90° between them.

A good betatron match between arcs is accomplished by adjusting designated quadrupoles in the recombiners. Two quadrupoles for horizontal matching and two are used for vertical matching. Quadrupoles used to correct the horizontal envelope function have positive gradients, while quadrupoles used to correct the vertical envelope function have negative gradients.

The idea is to adjust (while using the air-core correctors to excite oscillations) the quadrupoles responsible for the horizontal or vertical betatron match so that the average level of horizontal or vertical normalized amplitude for each arc remains constant throughout the entire accelerator.

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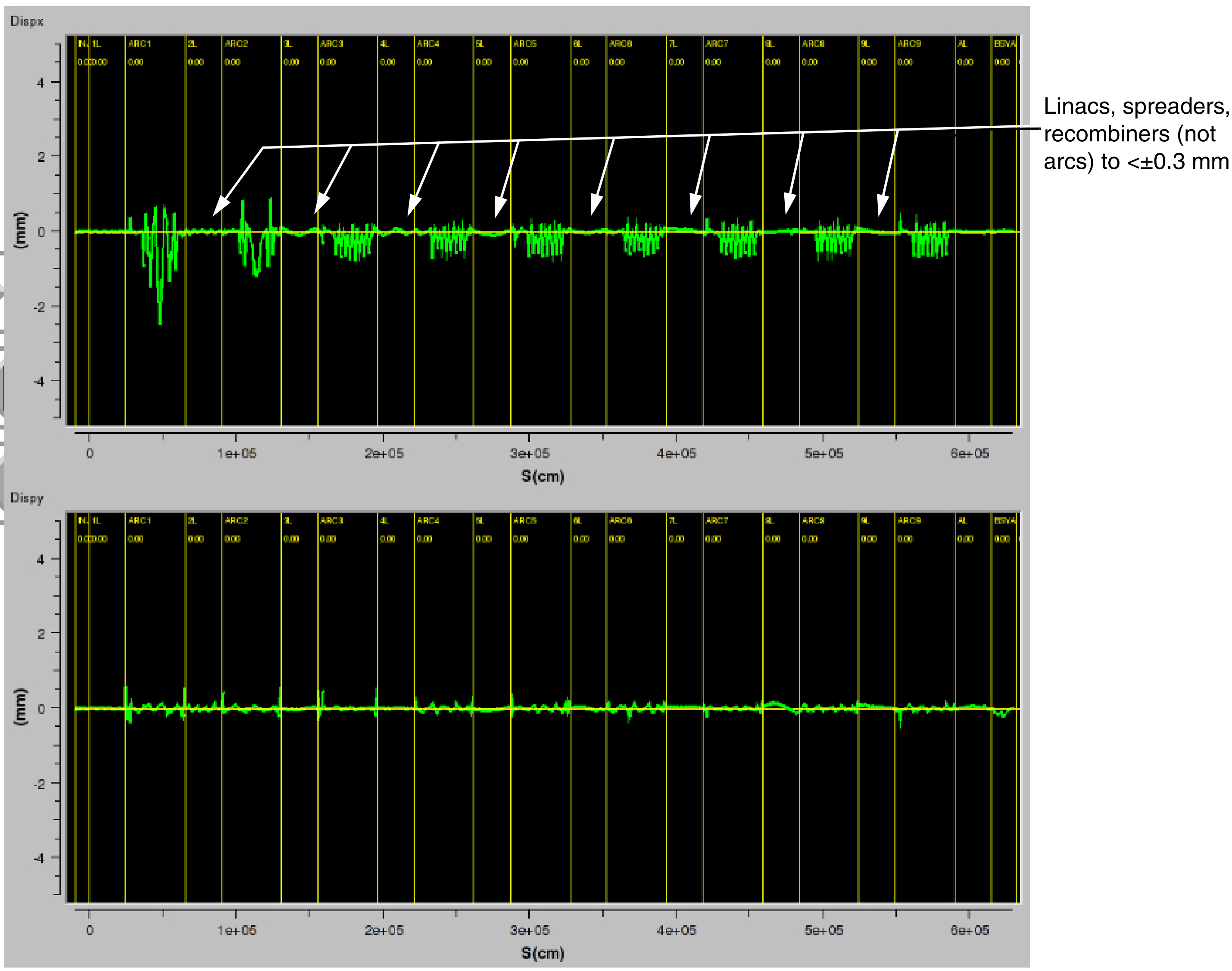
While performing the match, it is useful to remember that, in theory, if the normalized amplitude decreases with beam acceleration for a perturbation by one air-core corrector, it will grow for a perturbation by the other air-core corrector (in the same plane—either horizontal or vertical). Generally, these normalized amplitudes degrade through the accelerator, and you will need to bring them back to design values.

Return to Section 8.0, Correcting the Betatron Match, on page 11.

Appendix D – Nominal Dispersion Patterns

The dispersion patterns shown in Figure 8-1, below, are examples of acceptable dispersion patterns for all arcs and linacs. Acceptable dispersion is horizontal spikes in the linacs, spreaders, and recombiners <±0.3 mm from zero (the arcs will show more dispersion, that's okay), AND vertical spikes within the linacs and arcs <±0.3 mm from zero. Arcs 1 and 2 will typically show more horizontal dispersion (6 meters) than Arcs 3–10 (2.7 meters). This configuration accommodates energy lock operation.

Figure 8-1: Examples of Nominal Dispersion Patterns



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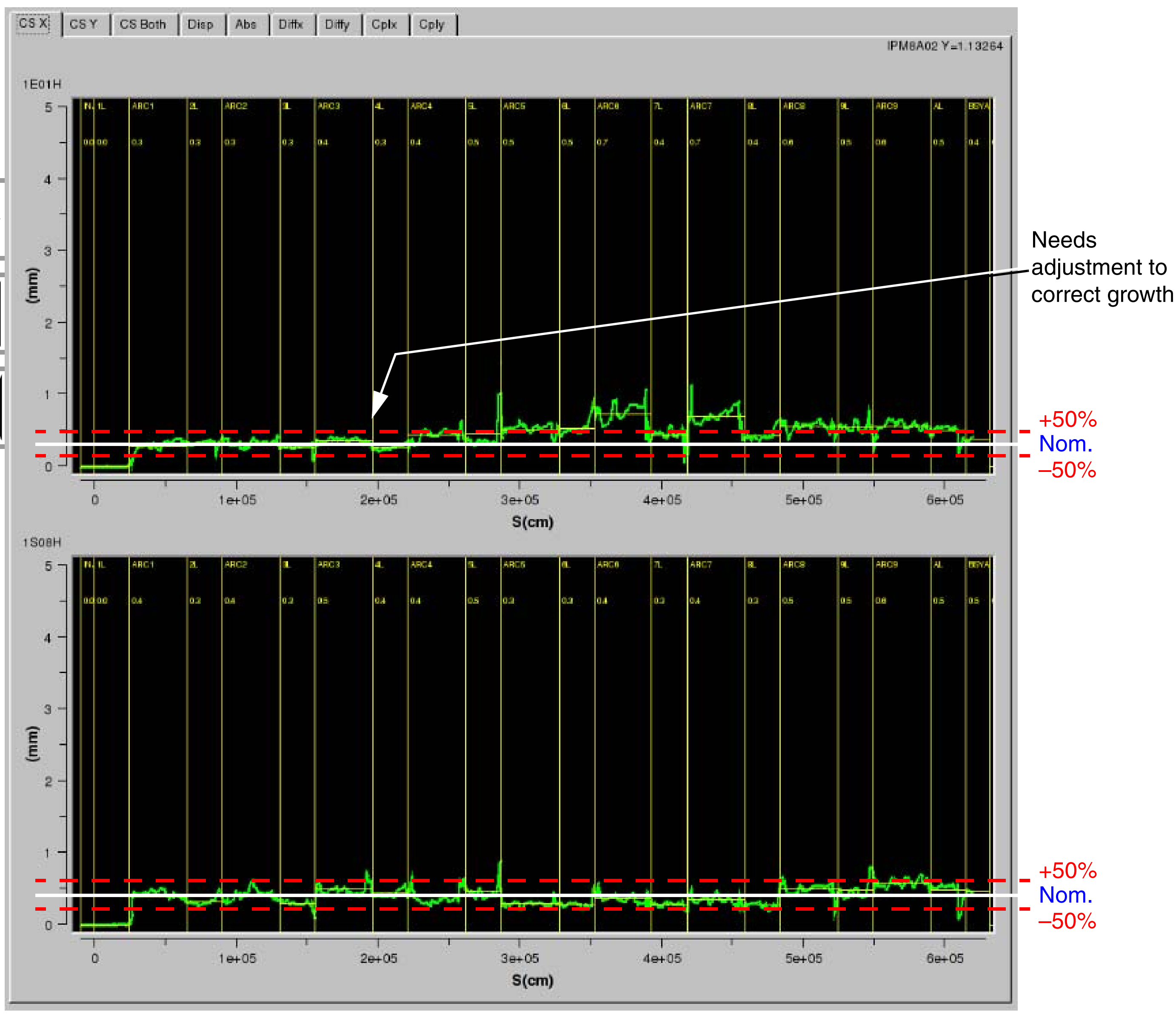
Appendix F – 30 Hz Normalized Amplitude Example

The 30 Hz normalized amplitude screen in Figure 8-2, below, shows an out-of-spec tune in the X plane with 1E01H excitation (top plot). The betatron function begins to grow in Arc 4 and is out of spec thereafter. The beam envelope must be adjusted to fall within the acceptable range of ±50% growth (or decay) across all arcs when compared to the nominal center line of Arc 1. Using the appropriate betatron matching quadrupoles, in this case in the Arc 3 recombiner, the downstream betatron growth can likely be suppressed. Additional downstream adjustments may be necessary, but always begin tuning just upstream of the growth pattern. The 1S08H excitation plot (bottom plot) is within spec, but as changes are made, you will want to balance the effects on both plots (top and bottom) to end up with an acceptable result.

Figure 8-2: An Example of a 30 Hz Normalized Amplitude Screen



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Appendix G – Procedure Flowchart & Quick Reference

All section titles at the top of the flowchart boxes are hypertext.

PREREQUISITES

1. 8 μA pulsed beam
2. All cavities phased
3. Cycle all quads
4. All magnets on loop (no alarms)

NOTE

1. Always take FOpt data **before** making any magnet changes, again as progress is being made, and then finally, **after** this procedure has been completed.

1.0 Initial Optics Check (p.2)

1. Check prerequisites (see list to left).
2. Check for prohibited quads (`CMPQ`). [If different from design, call Optics—see Step 2 on page 2].
3. Check injector-to-NL match. [If spots >2:1, fix injector match.]
4. Run locks and check orbit vs. standard.bpm.snap. Relative orbit <0.5 mm? [Bad: go to Section 2.0, page 4.]
5. Pathlength Δ ≤0.5°? [Bad: go to Step 10 on page 6 in Section 2.0.]
6. X-Y coupling—is motion in unexcited plane < half of that in excited plane? [Bad: Go to Step 2 on page 7 in Section 3.0.]
7. 30 Hz dispersion pattern nominal (<±0.3mm) in non-dispersive regions? [Bad: Go to Section 5.0, page 8.]
8. C.S. betatron plots okay (vary <±50% across all arcs compared to nom. Arc 1 center line)? [Bad: Go to Section 8.0, page 11.]
9. Optics okay if all preceding conditions are satisfied.

2.0 Restoring the Orbit (p.4)

1. Verify the golden orbits for locks and then run locks until they converge to targets.
2. Check the rel. orbit vs. standard.bpm.snap. Deviation must be <0.5 mm in arc.
3. Optimize orbit in downstream recombiner, linac, spreader using allowed correctors (Table 2-1 on page 6).
4. Cycle correctors that were changed.
5. Recheck orbit.
6. Repeat above steps for all arcs.
7. Check path length Δ (≤0.5°).

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3.0 Checking & Correcting X-Y Coupling (p.6)

1. Check for X-Y coupling with 30 Hz spikes. Motion in unexcited plane should be <1/3 of that in excited plane.

To Correct X-Y Coupling:

1. Use the Skew Quad Scaling tool (Arcs 1–7) or specified skew quads (Arcs 8–9).

4.0 Measuring Dispersion (p.8)

1. 30 Hz V & H absolute spikes ≤±0.3 mm in non-dispersive regions?

yes → 6.0 / 7.0

no → 5.0

5.0 Correcting Vertical Dispersion (p.8)

1. Zero pos BPMs.
2. Minimize vert. disp. in arc using nS01 quad **(except Arc 9)**, see Table 5-1 on page 9.
3. Iterate (n-1)R10 (±100 G-cm) to achieve best vert. dispersion **(Arcs 2–9 only)**.
4. Iterate Steps 2 and 3 to minimize dispersion.

6.0 Correcting Horizontal Dispersion (p.9)

1. Check horiz. dispersion quads vs. cmpq.
2. Open 30 Hz spike screens for arc and downstream arc.
3. Use one Group 1 & one Group 2 horiz. dispersion quads to minimize horiz. dispersion (see Table 6-2 on page 10).

7.0 Measuring and Correcting M56 (p.10)

1. Set phase slider to achieve zero crossing.
2. Set amplitude slider to 0.612.
3. Reset zero crossing & print wave form.
4. Turn off orbit lock.
5. Decrease linacs to dp/p = 0.001.
6. Print wave form.
7. Path length Δ ≤0.5°? If no, add +100 G-cm to specified quads.

8.0 Correcting the Betatron Match (p.11)

1. Make C.S. betatron plots. Plots should vary <±50% across all arcs compared to nom. Arc 1 center line

To Correct Betatron Match:

1. Select 1S08H.
2. Observe X plot and adjust the horiz. beta-matching quads, see Table 8-1 on page 12.
3. Select 1E01H.
4. Observe X plot and the horiz. beta-matching quads.
5. Optimize in X between 1S08H and 1E01H settings.
6. Check spots in downstream spreader (<2:1).
7. Repeat above steps for vertical beta match (1S09V and 1E01V).
8. Optimize balance between horz. and vert.

Verify the setup by repeating the Initial Optics Check