Correction Mechanisms for
Synchrotron Radiation Energy Droop
in Beam Transport at CEBAF

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Abstract: We present considerations on Synchrotron Radiation (S.R.) induced energy droop of the beam in the CEBAF transport arcs, particularly Arc6 and above plus the Hall transport lines. This discussion is specific to the effect of the slowly varying beam energy along dipole strings. We conclude that only the main accelerator regions Arc8/Arc9/ArcA require special attention to the energy shift. Beam line correctors require sparse peaks of 10%-20% of their capacity to control the beam position in even Arc7, with most requiring much less than this. Hall lines compensation requires very little strength because the peak energy mismatches are small. We consider a suggestion by L. Harwood to distort the transport arc into a spiral to avoid active compensation of the dipoles, and conclude that the offsets involved are probably prohibitive for already-installed arcs. We summarize and extend previous informal proposals for a simple coil compensation scheme, and provide approximate hardware costs. We recommend active compensation for Arcs 8 and 9 in a fashion similar to that considered here, and recommend that ArcA (arc 10) be treated in the same way to maintain better uniformity of operational setup procedures.

Changes at Higher Energy: In the higher energy 12 GeV future of JLab, the electron beam will emit Synchrotron Radiation at non-negligible levels. For arc 9, for instance, at 9.932 GeV approximate energy, the energy lost in transit of the arc will be approximately 16.7 MeV, or 0.00168 of the total energy.

Scale of Energy Droop: The present specification for the 12 GeV steering (to limit the RMS steering error in blind spots without BPMs to 0.6 mm) calls for a dipole bending angle variance of no more than 0.0005 of the nominal angle. The uncorrected S.R. energy loss contribution to variance in bending angle for arc dipoles, referenced to the average energy of the beam in the arc, is roughly (maximum deviation)/sqrt(3), numerically 0.00048~=(0.00168/2)/sqrt(3) for Arc9. This is a systematic, smoothly varying steering error, as opposed to the random variation used to determine the steering allowance. With a variance of this character, one might expect the RMS beam orbit excursion to be somewhat less than 0.6 mm. We show what happens below. The fractional energy droop of Arc6 and Arc7 are nearly equal at 0.00085, only a factor of two lower than that of Arc9. ArcA, with a droop of 0.00177, is not much different from Arc9.

The bending angle per meter in the Hall lines is close to that in ArcA. The Hall dipoles sum to 24 m in length, or 6/32 of the ArcA line in magnet length. The peak relative energy loss in the Hall lines is equivalent to 3/16 of the ArcA loss, and less at lower energy extraction. The peak A/C loss is 0.00033.

Arc	dE/E0	dϵ(nm-rad)	dE(MeV)
5	0.00050	0.17	2.8
6	0.00085	0.3	5.68
7	0.00084	0.37	6.52
8	0.00127	0.54	11.2
9	0.00168	1.07	16.69
10	0.00177	1.17	19.55
Halls	0.00033	-	-

Table 1: Relative energy droop, emittance increase, and absolute energy droops for selected machine regions

Three parts in 10^4 is a fairly small number, and correction of the Hall A 9^{th} dipole system output for this droop should introduce little additional error. The peak dispersive BPM offset from a relative momentum error of ±0.00016 (at the characteristic 4 meter dispersion) would be only 0.64 mm, and the momentum change is well-understood. The effect of the droop in energy is shown in Figure 1, an beam line modeled with Optim [1]. The vertical scale in all of these Optim examples is ±0.05 cm, or ±500 microns.

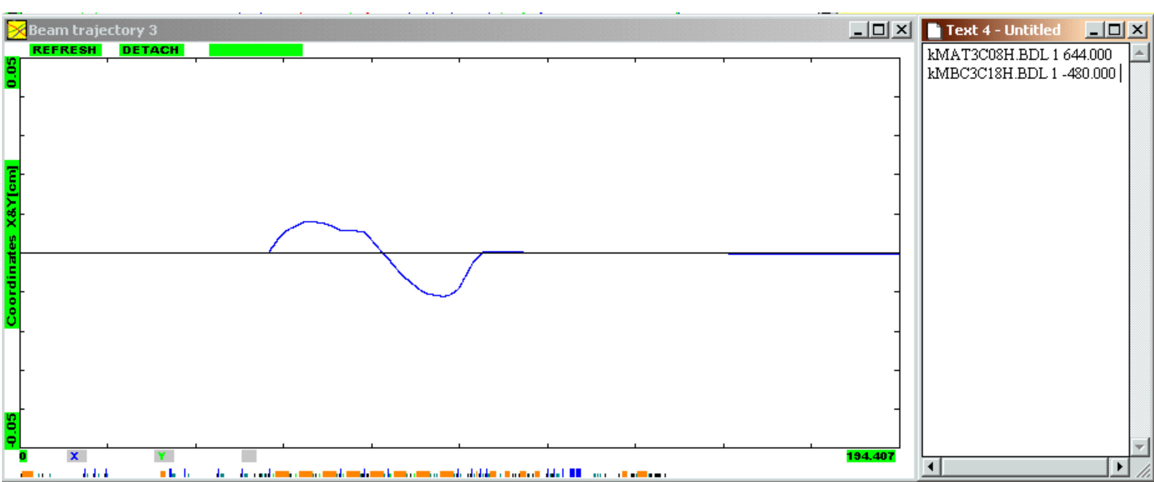

Figure 1: Hall C with energy droop. The small droop in energy results in mis-steering, not a dispersion change. Correction with steering elements only at entrance and exit from the arc for matched average energy keeps the maximum excursion to the 100 micron level. All Optim graphs here span ±500 microns.

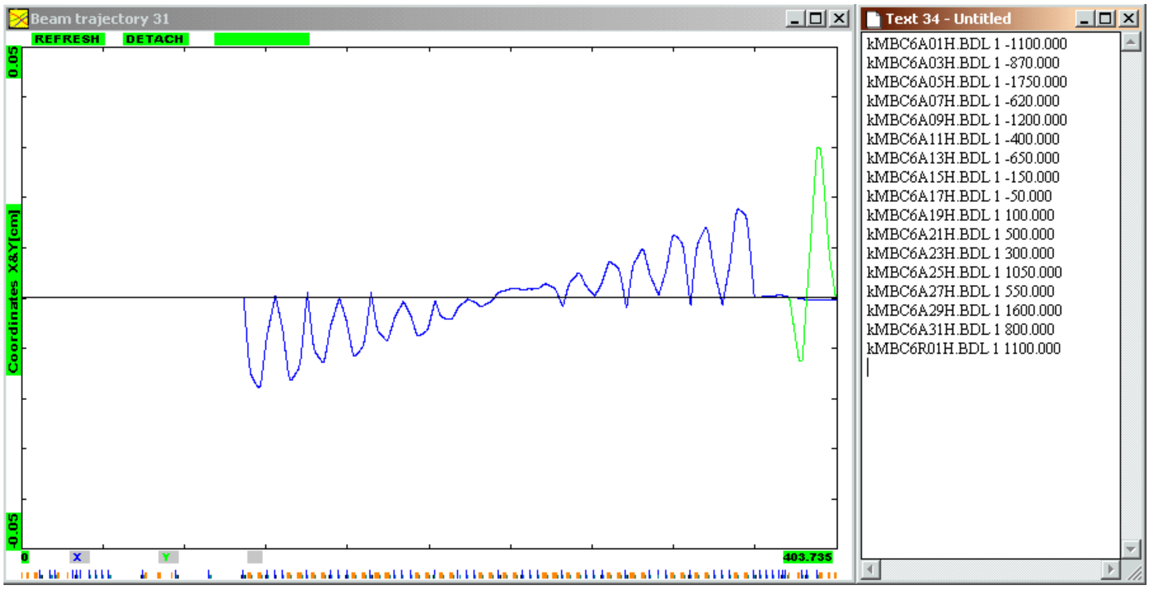

Figure 2: Arc6 manually re-steered for S.R. energy droop. Peak corrector strength available is 11600 G cm. BPM readings were approximately zeroed. Graph full scale is ±500 microns. The green "bump" is the vertical position shift in the Recombiner dipole step resulting from the energy shift.

The droop in energy as the beam transits the Hall C arc results in an exit steering error, but no change in the dispersive character. By re-steering at the entrance to the dipoles to zero the beam position near the 3C18 BPM, the beam position inverts as it transits the second half of the arc. As the beam crosses zero position at the 3C18H corrector, the correction is completed. The peak excursion is at the 100 micron level. This would be invisible to operators using existing procedures. It appears that there is no need for energy droop correction in the Hall A/C lines. The effects are even less for Halls B and D. We now examine the necessity of correcting for S.R. energy droop in Arcs 6/7/8/9/A.

The correctors in Arcs 6-9 are MBCs, and Arcs 6 and 7 have significant margin in available bending moment. Only two Arc6 correctors require no more than 10% of their strength to correct the S.R. induced dispersive offsets (see the values in Figure 2). With the BPM readbacks near zero, the RMS orbit error in regions with potential multipole field errors is under 200 microns peak and 100 microns RMS. See Figure 2 for an illustration from Arc6. If deemed appropriate, the non-uniform correction pattern could be managed and tracked as an energy dependent overlay to avoid operator confusion.

An example for Arc6 with 100 micron level peak offsets is in Figure 3, with very similar corrector settings. Both have 0.1776 MeV per dipole energy droop in the illustrations. Arcs 6 and 7 have very comparable energy droops, and appear not to require special correction for this effect. Only arcs 8/9/A appear to warrant special attention.

For Arc9, an Optim simulation with 0.522 MeV loss per dipole (again placed downstream from each dipole) required more than half of the available range of correction by 5 of the MBC horizontal correctors, one of which required full-scale excitation. See Figure 4. This figure shows the result for steering to zero on each BPM. Residual orbit errors increase through the arc (growing with energy error) and peak at 0.75 mm. If one were to minimize the anticipated RMS excursion instead of the indicated BPM excursion, the peak corrector strengths would be somewhat reduced.

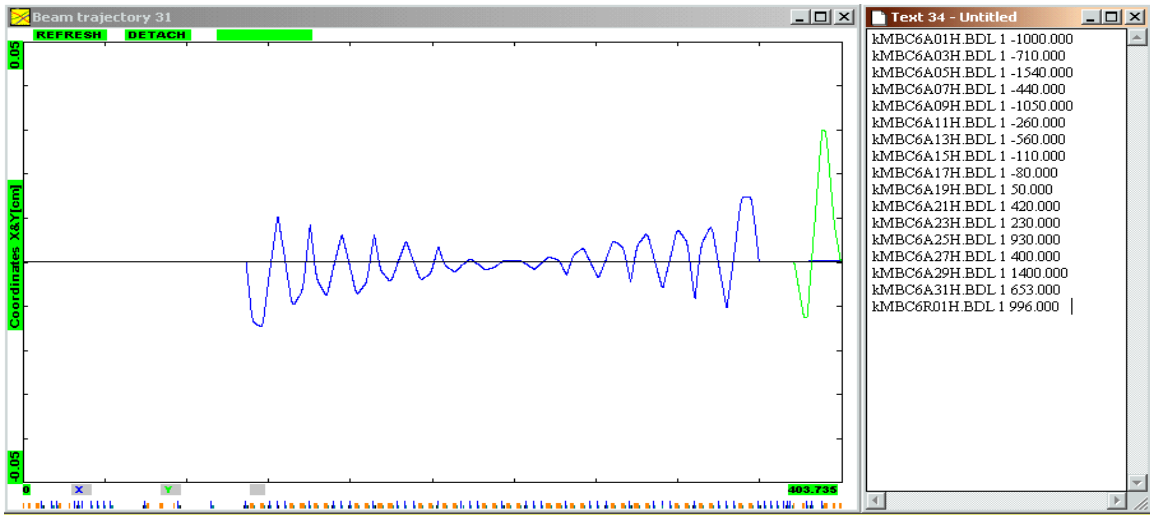

Figure 3: Arc6 with BPMs set to nonzero values because of external information about the energy droop. The corrector strengths are somewhat less than for Figure 2. Residual RMS orbit offset is approximately 100 microns. Arc7 orbit error looks identical because it has the same relative energy droop (see Table 1).

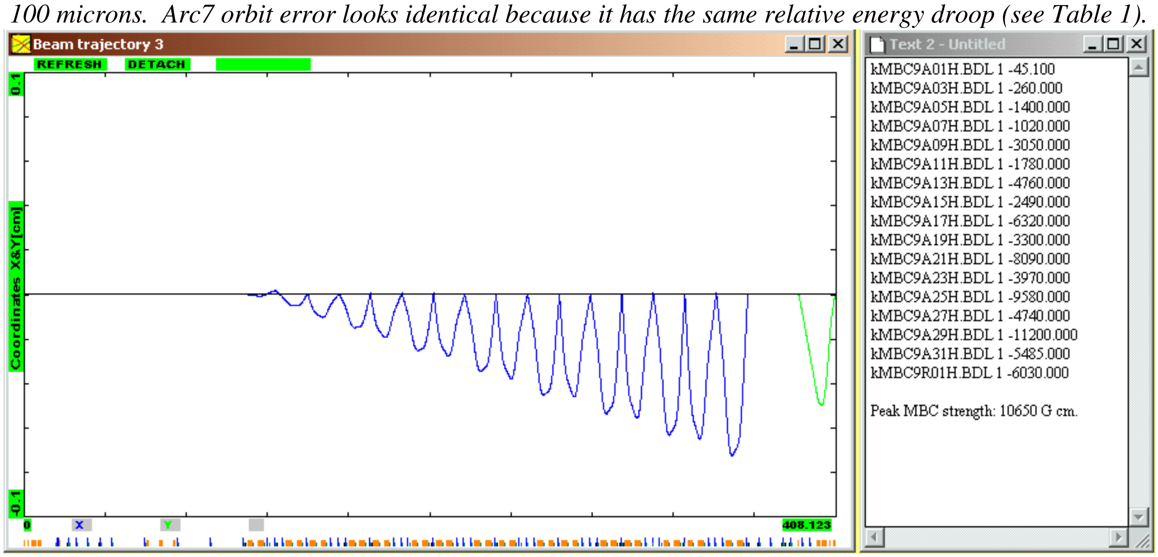

Figure 4: Arc9 corrected for S.R. energy droop, energy matched at entrance. BPMs manually zeroed as operators would do. This figure has a scale of ±1 000 microns, rather than ±5 00 microns of the others.

The result of setting the Arc bus to match the energy at the arc mid-point is shown in Figure 5. The extreme corrector values are about half of full-scale. The largest residual orbit errors are about 0.4 mm, and the RMS orbit error in dipoles and quadrupoles is about 250 microns. In order to accomplish the RMS steering goal of 600 microns, it may be advisable to correct the S.R. droop at the source in Arcs 8/9/A.

Correction methods: We have illustrated the use of beam line correctors to correct the orbit. Other methods of correction have been suggested, such as

1. individual correction shunts on the dipoles,
2. small gauge correction coils connected in series through all of the dipoles as a single correction parameter, and
3. accommodating a particular energy by distorting the arc, supplementing with beam line correctors at other energies (suggested by Leigh Harwood).

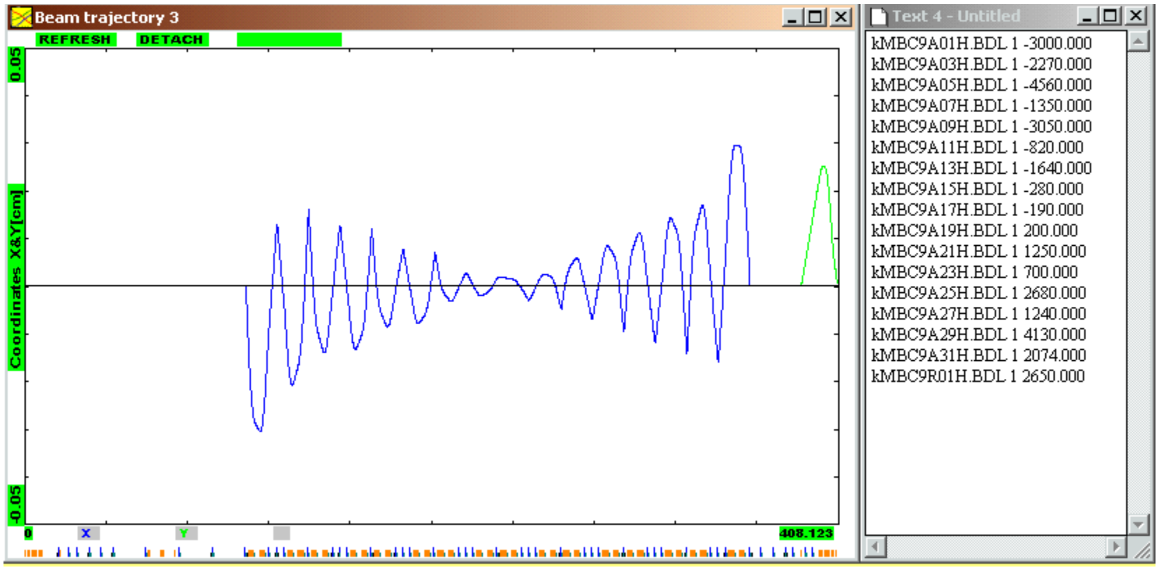

Figure 5; Arc9 manually re-steered with knowledge of S.R. energy droop, energy matched at mid-point of arc. BPMs not zeroed. Corrector excitation <=20% for most correctors.

Option 1. appears to be expensive, although each shunt might control groups of dipoles, using very few shunt modules per arc. Following the layout in the option 2 discussion below, one might need four or fewer shunts per arc. The operational complexity of multiple controls could be hidden and associated errors prevented by coupling the multiple shunt controls in a single high-level control point.

For option 2, an ideal correction scheme would use 31 turns in the first of 32 magnets, 29 in the next, and so forth through the 16th magnet. The last 16 magnets would have the same pattern, but inverted in polarity. The first dipoles would have their current supplemented, but the supplementary current in the latter half would buck out a small portion of the bus current. This pattern:

```
+31 +29 +27 +25 +23 +21 +19 +17 +15 +13 +11  +9  +7  +5  +3  +1 --->
 -1  -3  -5  -7  -9 -11 -13 -15 -17 -19 -21 -23 -25 -27 -29 -31
```

provides ideal correction using different 16 different coil configurations, and has zero mutual inductance with the main dipole string. The RMS steering variance of this layout is zero. Coarser layouts, with coils in pairs, triplets, etc, are schematically represented in Figure 6, overlaid with the exact compensation.

Of these, a layout with eight groups of four coils (only four different turns counts) has the interesting feature that the only applied correction needed is at the ends of the arc, just as happens for Hall C in Figure 1 above but spanning the whole arc. This layout can equivalently use turns counts of
`+7+7+7+7,+5+5+5+5,+3+3+3+3,+1+1+1+1,-1-1-1-1,-3-3-3-3,-5-5-5-5,-7-7-7-7`
or
`+4+4 +3+3+3+3 +2+2+2+2 +1+1+1+1 0 0 0 0 -1-1-1-1 -2-2-2-2 -3-3-3-3 -4-4.`
Only the second is illustrated in Figure 6. In real life every corrector will be used, as for today's machine, so there is no special gain attached to this layout.

From a simplicity of fabrication/installation standpoint, either a modification of the sextuplet layout of Figure 6 or a similar octuplet coil layout looks attractive. In the ideal sextuplet layout, the center six dipoles have no compensation, the next six to either side need one turn, the next six on either side get two turns, and the outermost single magnet on each side gets three turns. There are 26 coils of three configurations: 12 single-turn coils, 12 two-turn coils, and 2 three-turn coils on an arc. The variation mentioned drops the third turn in the outermost dipole compensation, so that there are no 3-turn coils. The variance added by this sextuplet configuration is only one part per ten thousand (0.0001), a very small contributor to the allowed 0.0005 random variance. This layout is equally applicable to Arc8 and ArcA.

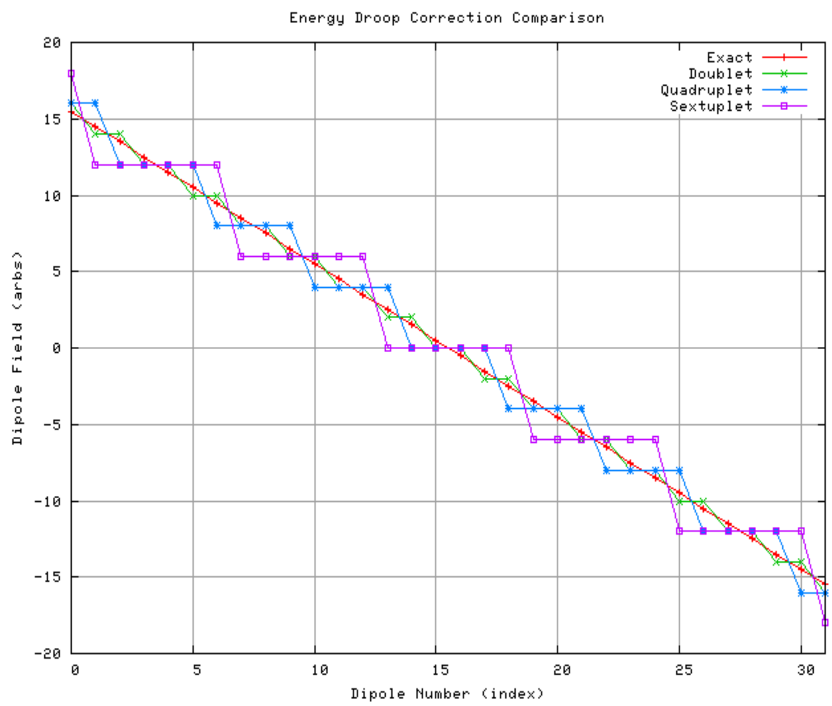

Figure 6: Comparison of several coil layouts for S.R. energy droop compensation. Odd numbered groups could have been used, too.

Optics modeling of the unmodified sextuplet layout is shown in Figure 7 for Arc9. It requires only 4% of the available corrector strength for correction. The variant using 2-turn coils for the outermost dipoles is shown in Figure 8. The outermost correctors use 6% of full range instead of 4%. The simplifications of having only two compensation coil types (single-turn and dual-turn, either polarity) and having the central six dipoles uncompensated make this very attractive. Note that the five correctors with zero strength occur at the center of sets of four consecutive dipoles with the same compensation, the same pattern seen in the Hall C line above in Figure 1.

I can't resist including an octuplet coil example, centered on eight uncompensated dipoles. These are flanked by eight one-turn coils (16 total) with the remaining two outboard groups of four dipoles having two-turn coils. The coil current required will be approximately 9 Amps (following the calculation detailed below calling for a 1.155 Amp turn decrement per dipole and dropping one turn per eight dipoles). This layout results in the model shown in Figure 9. The peak residual position errors are about 70 microns (with positions zero at BPMs) and only half of the correctors are used, and at quite low fields. Only 24 of the 32 dipoles have compensation coils appended.

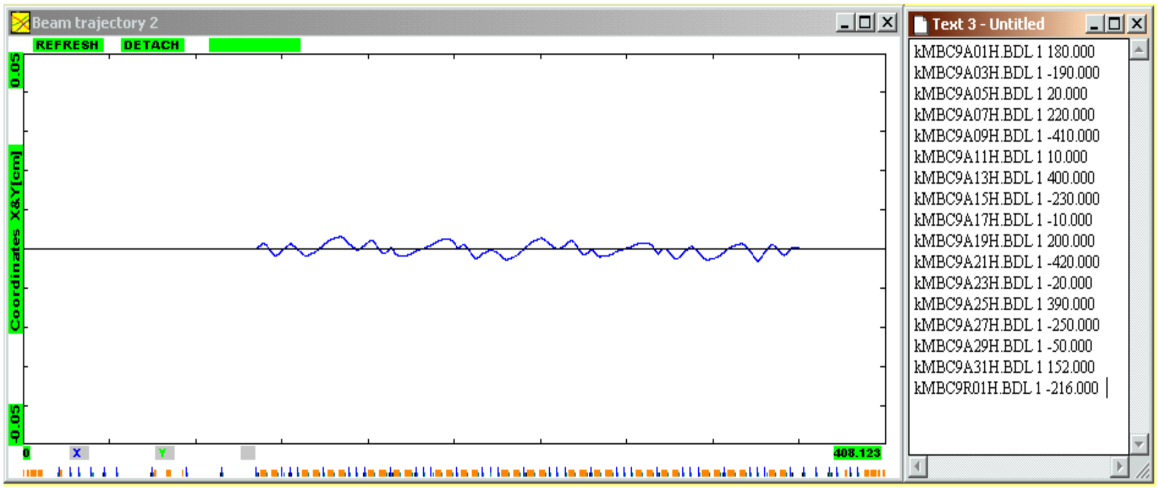

Figure 7: Arc9 with sextuplet correction coils, steered to zeroes on BPMs by hand. Residual orbit error from S.R. energy droop is at the 50 micron scale. Corrector strength required is under 4% of full scale.

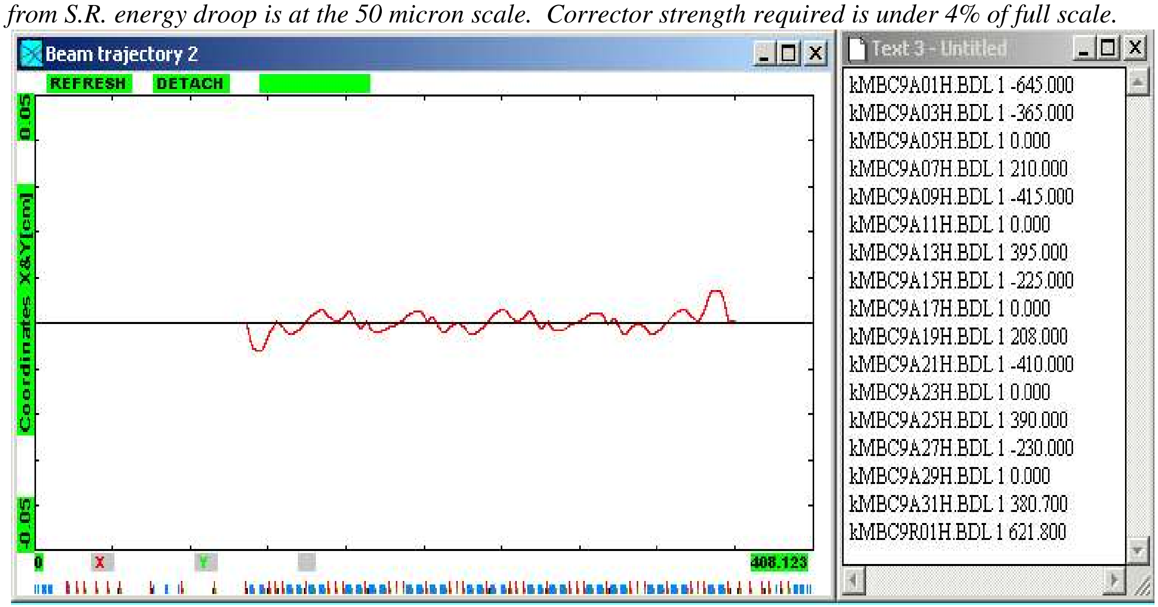

Figure 8: Modification of sextuplet compensation with outermost dipole coils using only 2 turns.

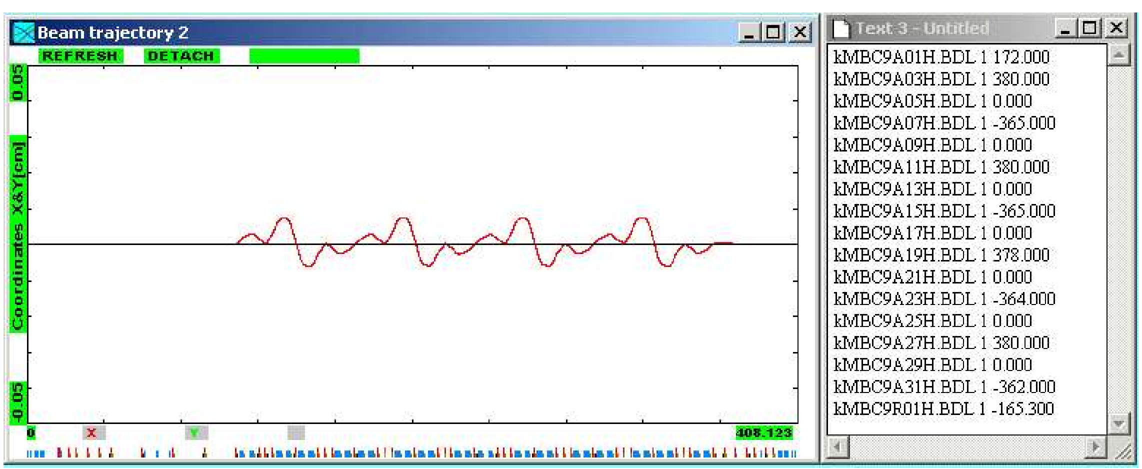

Figure 9: Arc9 with octuplet coil layout. Eight uncompensated dipoles at center, eight 2-turn coils to left and right, with four 4-turn coils at either end of the arc. Residual orbit errors peak at 70 microns.

Coil Parameter Example: With an arc bus current of 550 Amps in 40 turns (appropriate for Arc9), the magnets have 22000 Amp turns. For the Arc9 S.R. droop of 0.00168 over 32 magnets, the energy loss per magnet is 0.00168/32, or 0.0000525. This corresponds to 1.155 Amp turn per dipole. Each group of six dipoles thus should increment by 6.93 amps, so this should be the current in the compensation coil wire.

The coils above in the modified sextuplet layout contain 40 total turns of wire, each of circumference approximately 9 meters (for 4-meter dipoles). Adding 9*40 m to the round-trip path along the arc, approximately 2*80*pi, the total wire length is approximately 860 meters (2820 ft). The total resistance should be less than 3.5 ohms to use a standard 30V trim card, so the resistance should be less than 1.24 ohms per thousand feet. Magnet wire of AWG #10 with 1 ohm per k-ft satisfies this quite well.
Such a coil configuration may be powered by a single trim card selected anywhere in the arc service buildings. AWG #10 magnet wire (I looked it up) runs 32 ft per pound, so the 3000 ft above should weigh about 100 lb. On magnet4less.com as of this writing, 11 pound spools of Essex brand AWG-10 varnished magnet wire are offered for $160. Nine spools will cost about $1500 and make up one arc. Connectors and slit loom (plastic insulation as for automotive wiring harness use; today's price from delcity.net is 10.5 cents per foot in 2000 ft lots for 3/8" fire-retardant wiring loom) will add to the cost of materials, but not dauntingly so. Direct costs for materials should sum to no more than approximately $3k per arc. Magnet modeling [2] has shown that positioning of the correction coils in the vicinity of the pole tips is not critical to field quality, especially at the currents involved, so fixturing precision is not critical.

The octuplet layout is made up of 16 one-turn coils and 8 two-turn coils (32 total turns). Adding up its total length plus the arc transit as before gives a total length of 790 meters, or 2600 ft. The 2.6 ohm resistance readily supports the 9 Amp current anticipated to be needed for this Arc9 configuration.

Geometric Distortion of the Arcs: Another aesthetically interesting option (suggested by Leigh Harwood) is to distort the arc geometry to match the declining beam energy for a particular beam energy. If this reference is chosen near the full energy bound, then the corrector contribution will be small for energy near the matched energy. Lesser energy configurations will require angular corrections of the scale mentioned above but at lower beam energy and proportionally lower field integrals. The required corrector excitation should peak at the half-energy point (50% of full 12 GeV settings) at approximately half of the levels shown in Figure 5 (peaking at roughly 1/4 of full scale MBC corrector strength).

The arc distortion will result from the beam bending relatively less for the first half of the arc and more for the second half. For ArcA, this will shift all elements toward the South Linac and away from the center of the accelerator. In the accelerator coordinate frame, call X the direction perpendicular to the linacs and Z along the linacs. The result for ArcA, as calculated using the “show orbit” feature of Optim, is a shift of the elements in the Z direction away from the accelerator center (outboard direction from the perspective of the arc bend) gradually increasing to 9 cm at the exit of the arc, accompanied by a shift in X (toward the South Linac) of the arc elements by amounts increasing up to 3 cm at the mid-point of the arc, then decreasing back to zero at the end of the arc. The 9 cm displacement of the arc end adds nearly 180 degrees of path to the beam travel, which may be readily accommodated by moving the entire arc in-board by ~4.5 cm. The result of this is shown in Figure 10. The results for Arc9 would be very similar.

Such a distortion an arc involves 3-5 cm scale displacement of all of the arc magnets with respect their present (semi-circular) positions. Irrespective of whether this offset is practical for Arc8 or Arc9, ArcA will have its own new stands and they may be set as desired at this level. ArcA is presently expected to be operated near full energy "most of the time," and so distorting it into a spiral as a passive solution appears defensible. Caveats to this include that 1) devices are not always used most in the way that the designers expect and 2) it is generally wise to make operational procedures uniform, rather than including deliberate and unnecessary "special cases" which require remembering exceptions.

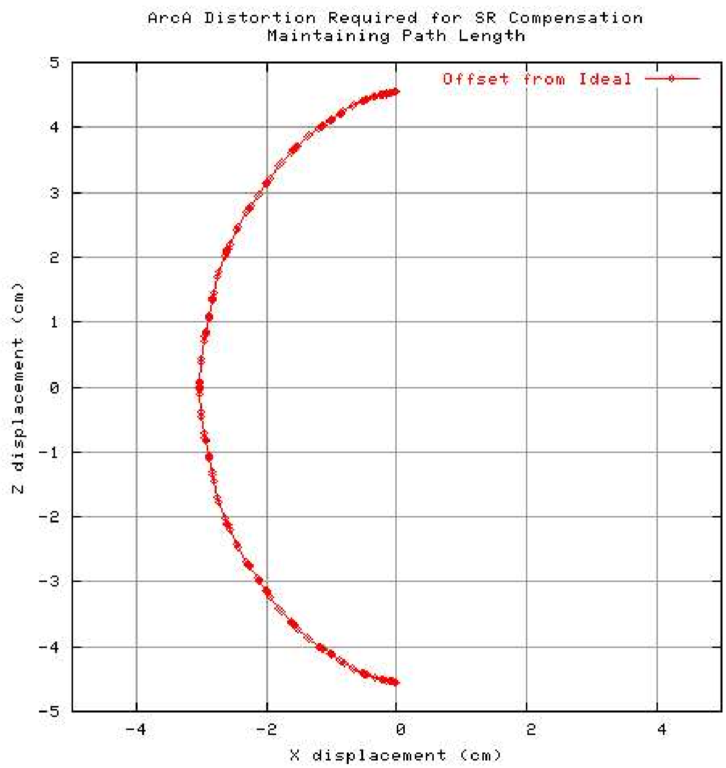

Figure 10: Distortion of ArcA to accommodate S.R. energy droop. The arc is offset in Z by 4.5 cm to maintain path length. As the arc straightens out slightly from its entrance at Z=-4.5 cm, the elements shift leftward and toward positive Z. The spiral sharpens to complete the 180 degree bend and bring the X position back to nominal, but the Z offset increases by 9 cm.

Consequences of choices: The anomalous dispersion introduced by distorting the arc is very nearly zero, and is not a concern. Once the arc geometry is set, it will not be readily changed. Operational issues of setting the arc dipoles will be affected by the choice made. A single correction parameter as for the series compensation coil option could be set strictly as determined by beam energy in the arc, with all further steering to thread beam being done as customary at JLab. Multiple correction knobs using independent correctors will require significantly non-zero "ideal" settings, varying strongly along the arc. The current practice of reducing the steering corrector strengths to "improve" the setup will no longer be as intuitively applicable.

Conclusion: Several means of compensating the arcs for S.R. induced energy droop have been suggested and considered. The regions appropriate for active compensation beyond use of the beam line correctors appear to be only Arc8/Arc9/ArcA. Arc6 and Arc7, the existing Hall A/B/C lines, and the Hall D line will suffer little because of the small cumulative energy droop in those shorter (or lower energy) lines. The optical consequences of all of the solutions appear to be acceptable, with the proviso that reducing the number of distributed controls is operationally more to be desired and that repositioning capacity for the existing optical components of Arc8/Arc9 may be limited.

It appears to this author that retaining the ideal beam line geometry and periodicity while matching the dipole excitation current to the drooping beam energy via compensation coils is the preferred solution, involving the least risk of error and greatest operational simplicity. Even for the special case of ArcA, which is most likely to be used at near full energy and have limited operational down-side for passive correction, uniformity of practice and procedure would argue for using correction coils rather than making it the only spiral arc. Location of the components in a spiral is physically feasible for ArcA because its stands are not yet in place, but this would make tuning procedures for ArcA different from the rest of the accelerator system when running in the lower portion of the energy range.

Recommendation:

This author's experience at JLab leads him to believe that leaving each of Arc8, Arc9, and ArcA as true semi-circles with a single correction knob using a set of series-connected correction coils is the preferred S.R. energy droop correction mechanism from a simplicity of operation standpoint. Appending series correction coils to Arc8/Arc9 while distorting ArcA as a passive correction would introduce unnecessary exceptions to control room procedures. The coil systems suggested with six or eight uncompensated dipoles at the center of each arc appear to have a nearly negligible direct cost and can be powered by single trim cards. When powered according to the beam energy in the arc, according to a well-defined relationship, the setup procedures will reduce to exactly those presently in use. This constitutes a very operationally defensible mechanism for correction of S.R. induced energy droop. Present procedures should serve in all regions other than Arc8, Arc9, and ArcA, with no new compensation being required.

References:

[1] – Optim: V. **Lebedev**, link below active as of this writing
http://www-bdnew.fnal.gov/pbar/organizationalchart/**lebedev/OptiM/optim**.htm
[2] – Magnet Modeling: Jay Benesch, JLAB-TN-08-027 – not yet issued at this writing