JLAB-TN-05-004
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Version 1: 05/05/05
Version 0: 10/12/04

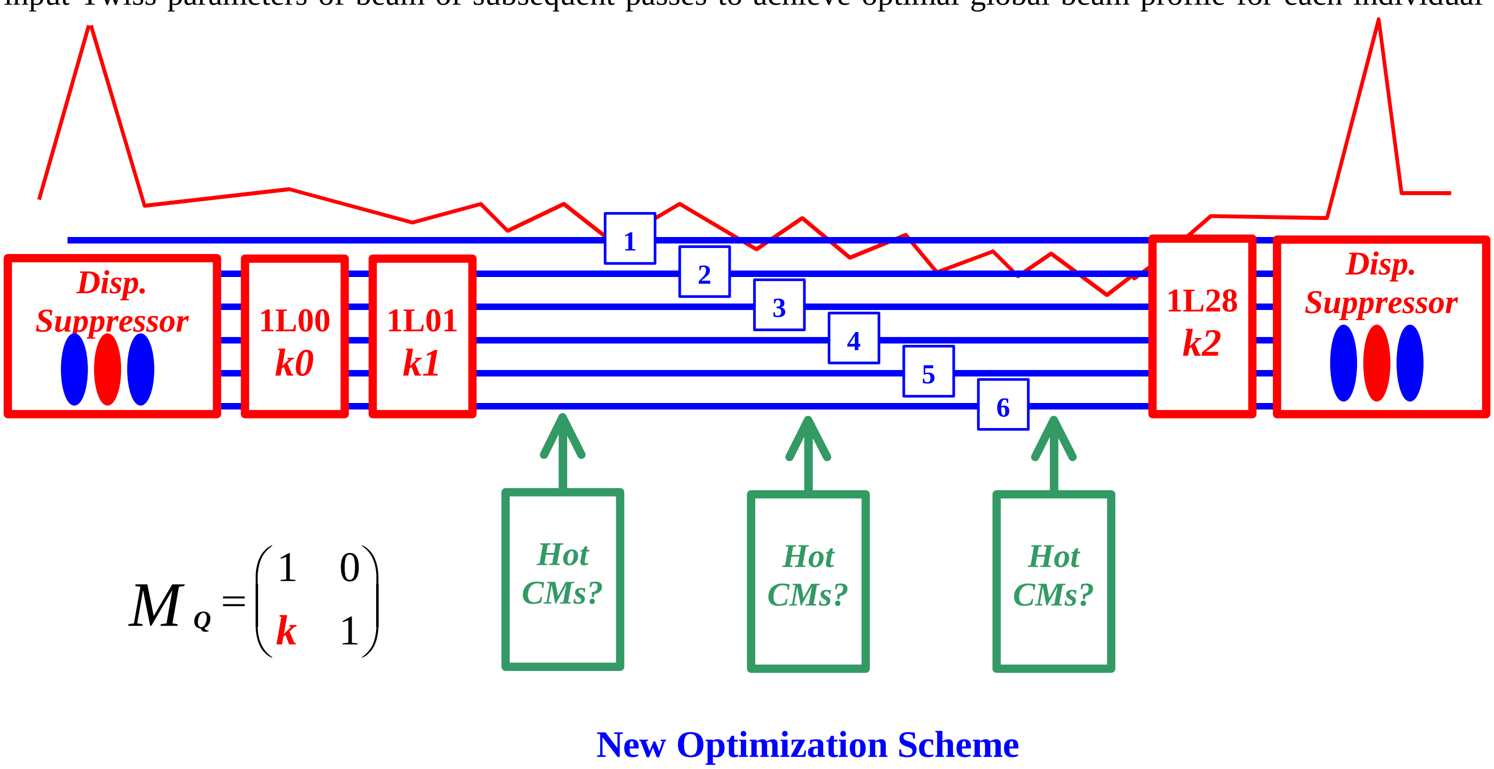
Improved Optimization of North Linac Momentum Profile for CEBAF 12 GeV Upgrade

Overview

The gain in maximum beam energy (from 6 GeV to 12 GeV) of the CEBAF upgrade is realized through five new cryo-modules (CM), each delivering 100 MeV, in addition to the existing 20 CM's for each linac[1]. The question of where these new "hot" cryomodules, or equivalently the linac momentum profile, should be located in the linacs deserves careful examination in order to arrive at an optimal trade-off between operability and cost. Operability issues that depend on the linac momentum profile include multiple pass matching and orbit sensitivity, and multi-pass beam breakup (BBU). This note presents a detailed numerical study of the impact on matching and orbit sensitivity based on various choices of the linac momentum profile.

The linac momentum profile has significant effect on the ease of achieving multiple pass matching, especially in the North Linac, due to the need to use common quadrupoles in the linac to contain beam profiles from all 6 (5 in the South) passes of widely disparate momenta. The larger the difference in beam momenta between passes at a given point, the more difficult it is to achieve simultaneous control of them. The worst possible ratio between beam momenta naturally happens near the entrance to the linac due to the relatively low momentum of the injected beam compared to the linac momentum gain. It is also where one can make the most impact on this ratio through varying the linac momentum profile.

The working strategy followed for a given linac momentum profile has been to impose a constant focal length FODO lattice with a fixed phase advance per cell (120° nominal) for the first pass beam, and adjust the input Twiss parameters of beam of subsequent passes to achieve optimal global beam profile for each individual



$$M_Q = \begin{pmatrix} 1 & 0 \\ k & 1 \end{pmatrix}$$

Figure 1. 6-Pass North Linac Recirculation & Concept of Optimization

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[1] Another contributor is the additional recirculation pass through the North Linac

pass. This strategy is adopted for the current analysis, with detail given in the following.

Method of Analysis

The goal of the optimization for any given configuration, involving not only the linac momentum profile, but also phase advance per cell for the first pass and possibly other features, is to find the combination of designated matching knobs controlling beam envelope in all 6 (5 in the South) passes such that the overall minimum in beam envelope (β) is achieved. This requires some explanation.

- The matching knobs available for controlling beam envelope in all 6 passes in the North Linac, after constraints are satisfied for Arc matching and dispersion suppression, are the two quadrupoles 1L00 and 1L01 (Figure 1). The quadrupole 1L28, while not conventionally used for this purpose, can also contribute toward this end. 1L00 and 1L01 have effect on the last 5 passes, while 1L28 has effect on all 6 passes.
- Consideration of global minimum beam envelope must take into account the upstream recombiners and downstream spreaders. This is especially true because the demand of vertical dispersion suppression virtually freezes the focusing patterns on both ends of the linac and caused the β functions inside the dispersion suppressors in the spreaders and recombiners to be the limiting factors of the entire minimization effort. This is conceptually shown in Figure 1.

The optimization therefore proceeds as follows. For a given configuration (linac momentum profile, phase advance per cell, etc.) a 2-dimensional scan is performed in the space spanned by the strengths of the 2 quadrupoles 1L00 and 1L01, or more precisely the M21 components of their respective thin-lens matrices. At each scan point the lowest achievable <u>peak</u> β function for both planes and all 6 passes is obtained, through a sub-scan over the 4-dimensional Twiss parameter space, in the region including not only the North Linac, but also the focusing quads for X and defocusing quads for Y inside the immediate upstream & downstream dispersion suppressors. This minimally achievable peak β as a function of the two scanned quad strengths defines the achievable beam envelope in both planes for all passes on the entire north end. By examining the 2-dimensional contour plot of this minimal peak beta one can conclude on the degree of difficulty to control the beam envelope either at design level or in real operation.

In the following results from optimization as described are presented under various North Linac configurations, consisting of the following possibilities:

- Cryo-module placement with the 100 MeV "hot" cryo-modules all at the front end, all at the back end, shared on both ends, or otherwise distributed throughout the linac (e.g., in the middle for CHL considerations);
- Phase advance per cell set to 120° or 150°;
- 1L28 quad set to various non-standard strengths.

Outcome of Optimization under Various Configurations

Particular attention is paid to the two cases with all 5 hot CM's at the front, and all at the end. Figure 1 shows this comparison, extending also to cases with the quad 1L8 set to different strengths. The first (second) column corresponds to three cases where the 5 hot CM's are placed at the end (front) with quad 1L28 set to 60%, 100% and 150% of the nominal value. Each diagram shows contour areas of different colors in the 2D parameter space spanned by the strengths of the quads 1L00 & 1L01 (represented by the M21 of their respective matrices). The contours are determined by the global minimum peak β[2] achievable, as indicated in the color legend (meter), for the particular combination of 1L00 & 1L01.

[2] Namely, the peak β for both lanes, all 6 passes, including West Recombiner, North Linac, and East Spreader.

The two cases with nominal 1L28 strength are further used for realistic rendition by Optim, complete with thick lens optics, actual machine dimensions, and matching into upstream and downstream Arcs[3]. The Optim-matched results are shown in Figures 3 and 4, and are in close agreement with those predicted by the optimization.

Several points are worth noting:

- With all 5 100 MeV CM's in the back end, the scan only produced one case (inside the yellow circle) with maximum β less than 300 m. This was used for the Optim matching, and is not expected to be too robust in keeping the global β below 300 m all the time.
- Nonetheless the new optimization scheme improved things compared to the original point design where global maximum β was 360 m even with all eight 67.5 MeV CM's in the front of NL.
- The β in the recombiners and higher pass spreaders is where one sees the largest difference between these 2 cases. The optics is clearly much more sensitive here with all 5 100 MeV CM's in the back end.
- Ease of matching to the Arcs, and thus overall quad strengths, are considerably improved with all 5 100 MeV CM's in the front end.
- It seems that quad 1L28 has a nontrivial leverage on the overall envelope. Matching into Arc 1 still needs be evaluated, but most likely we can gain a little here.

[3] Remember the West Recombiners are not final at this point, although the difference should not change things too much.

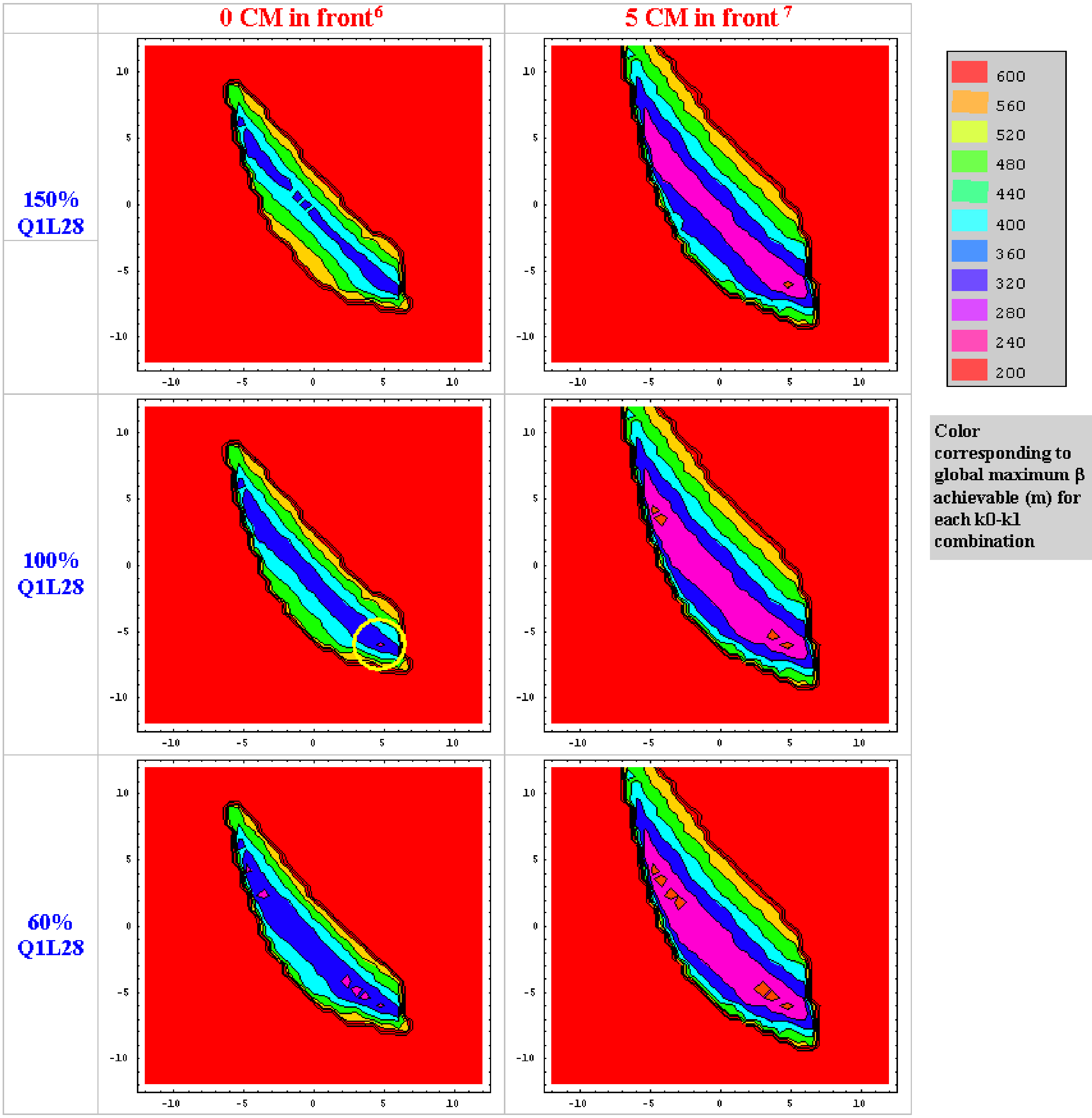


Figure 2. 6-Pass North Linac Recirculation & Concept of Optimization

[4] Global matching solution presented below is based on the single solution (magenta dot inside yellow circle) which is the only solution found with global β less than 300 m.

[5] Quad strengths are reduced across the board (Spreader, Recombiner, Re-injection Chicane) for the case with all 5 hot CM's at the end of NL.

Figure 3. Pass 2-6 Recombiner-North Linac-Spreader Optics (Vertical Scale: 300 m)
5 Hot CM at end All matched to up/downstream Arcs

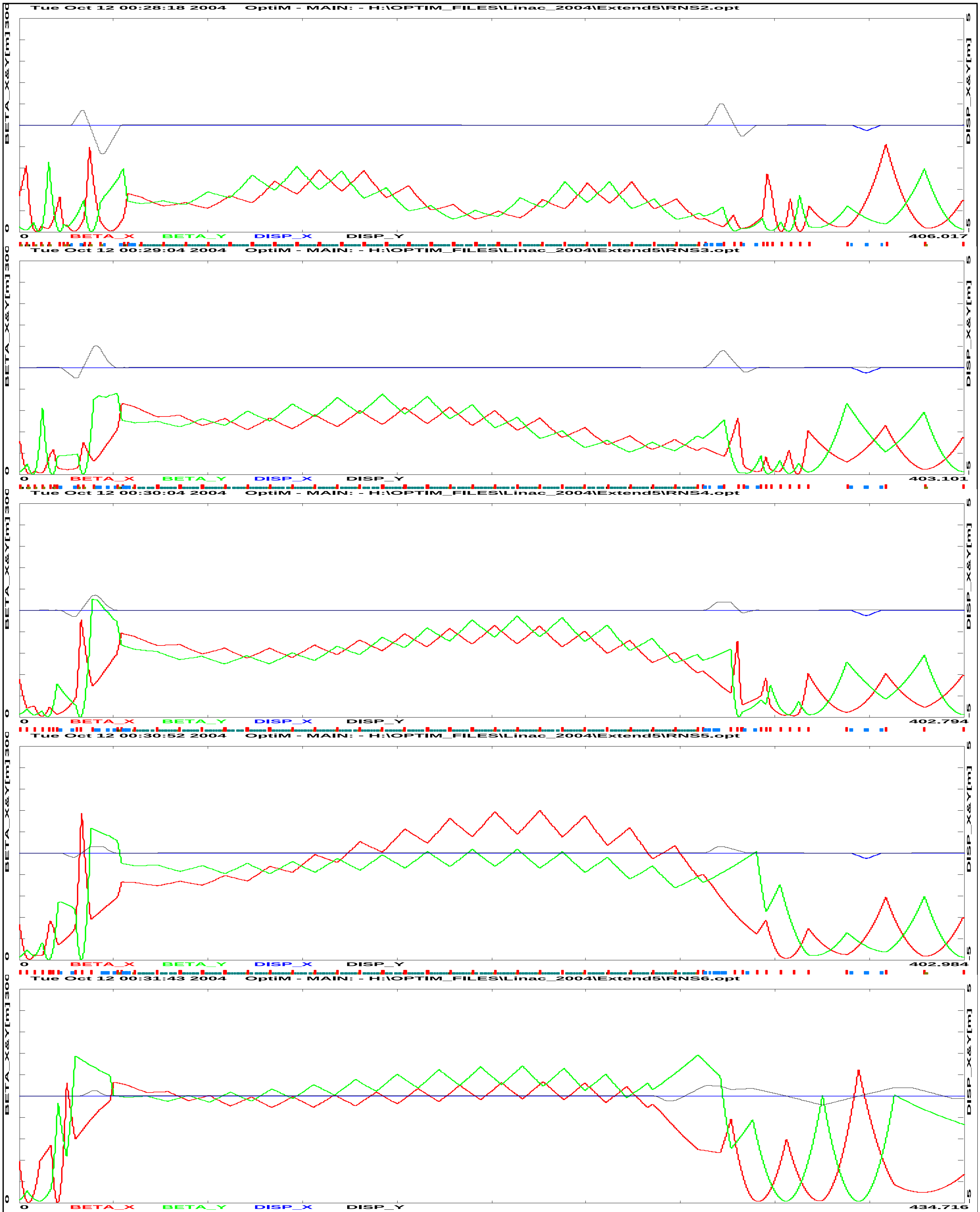


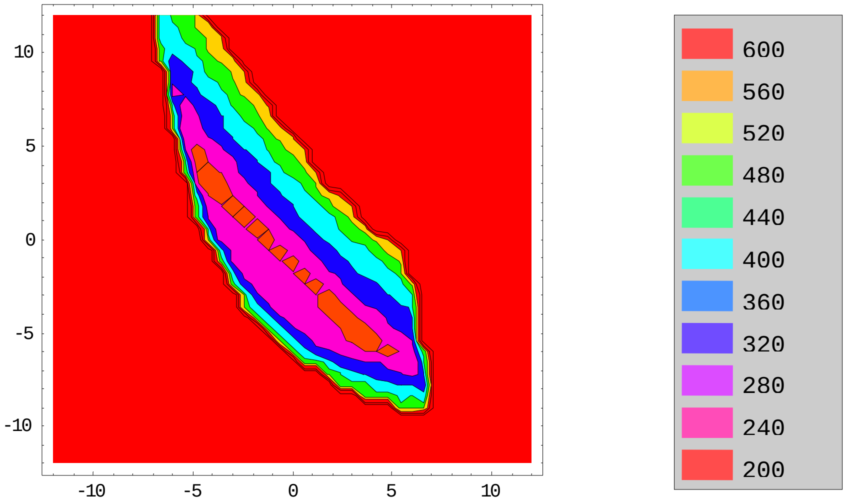
Figure 4. Pass 2-6 Recombiner-North Linac-Spreader Optics (Vertical Scale: 300 m)

5 hot CM in front All matched to up/downstream Arcs

Other Scenarios

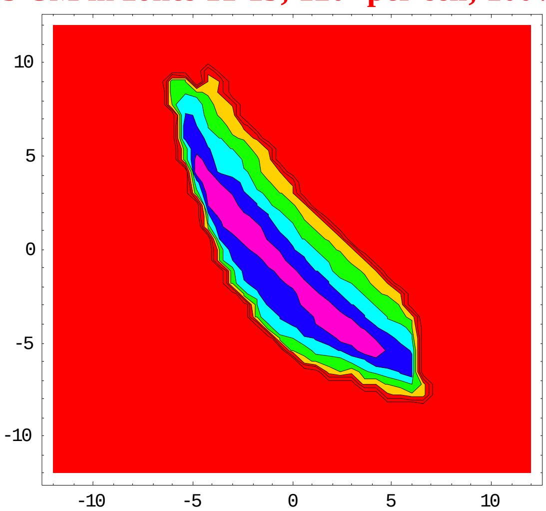
Some additional NL configuration options are subjected to the same procedure of 2D quad strength scan plus envelope optimization. These are given below:

5 CM in front; 150° per cell; 60% Q1L28



<u>This is the ultimate optimal NL configuration in the context of global matching</u>. There is a sizable area where the global maximum β stays within 200 meters! This should be borne out by more detailed Optim from experience above.

5 CM in zones 11-15; 120° per cell; 100% Q1L28

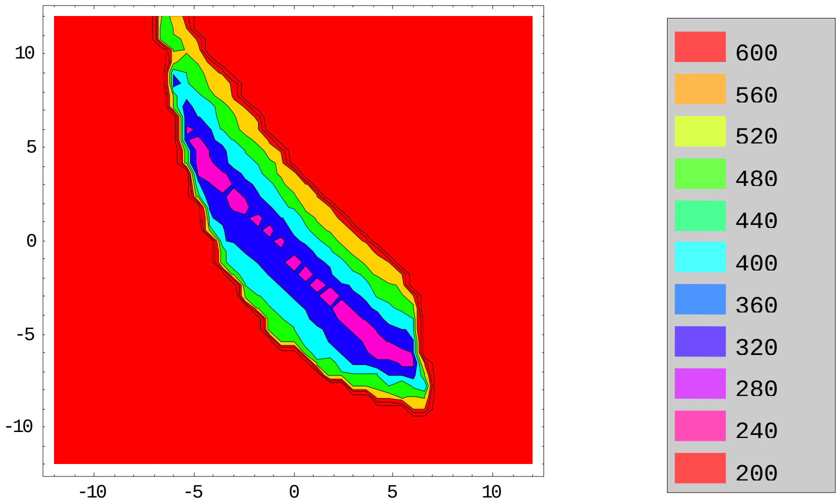


This places the 5 100 MeV CM's in the middle of an otherwise nominal NL. As expected the performance is mid-way between the 2 extremes studied in detail above.

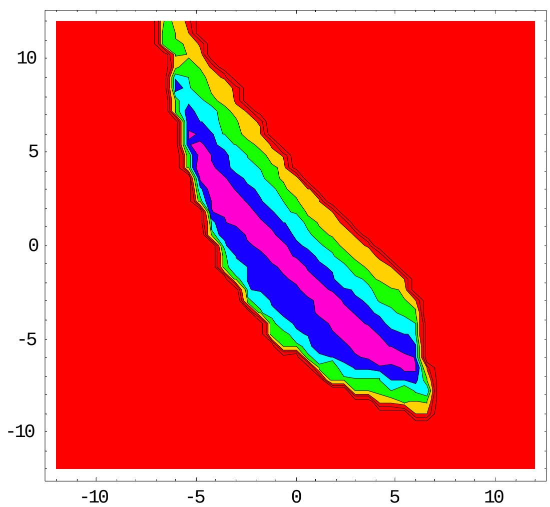
Split CM placements

This is the case with 2 100 MeV CM's in the front and 3 in the back end, also studied in the previous optimization mainly due to the need to trade-off with BBU effects. It does not seem to be as urgent now based on Byung's observation.

2 CM in front & 3 in back; 120° per cell; 100% Q1L28



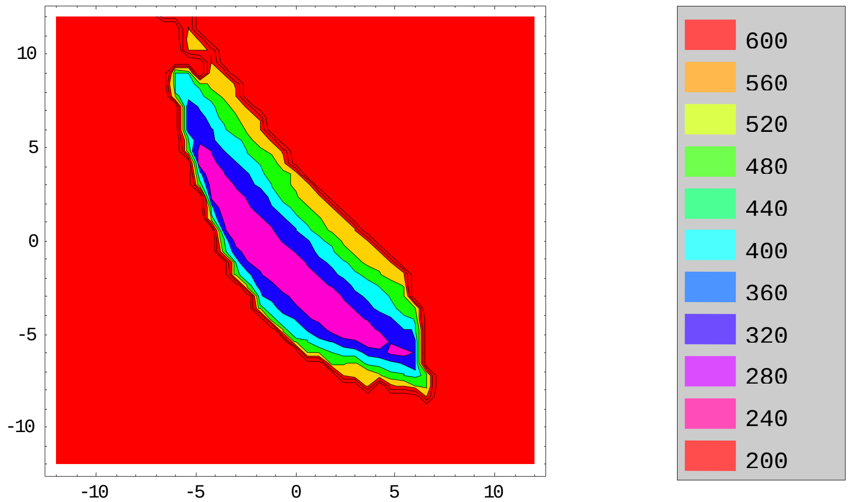
2 CM in front & 3 in back; 120° per cell; 60% Q1L28



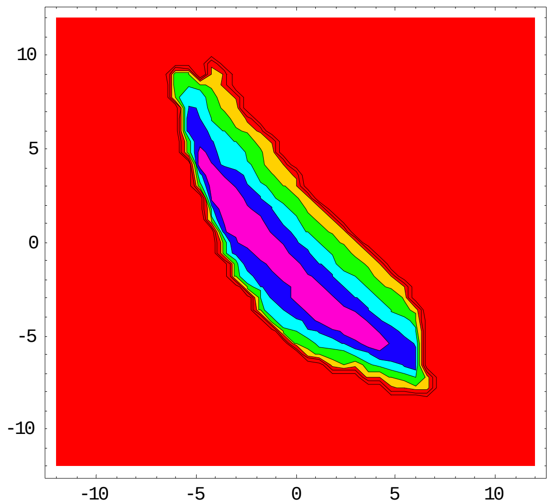
Center-located CM's

Two more cases with center-located 100 MeV CM's.

5 CM in zones 11-15; 150° per cell; 60% Q1L28



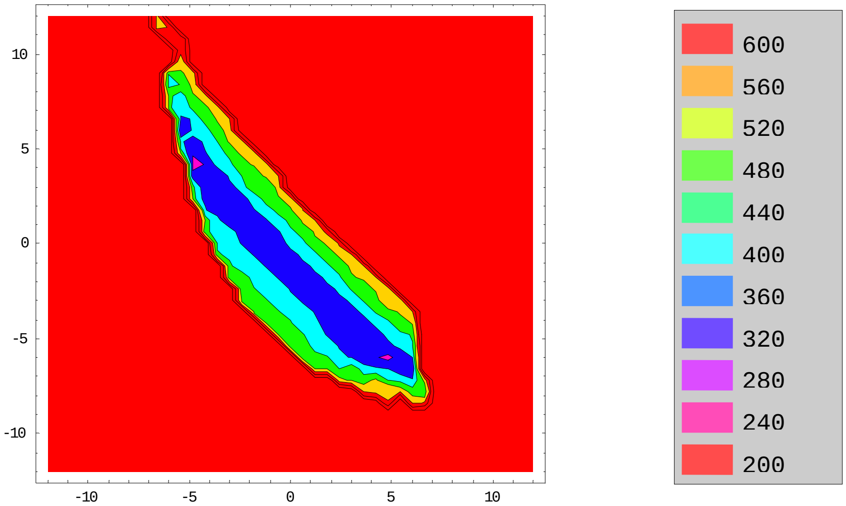
5 CM in zones 11-15; 120° per cell; 60% Q1L28



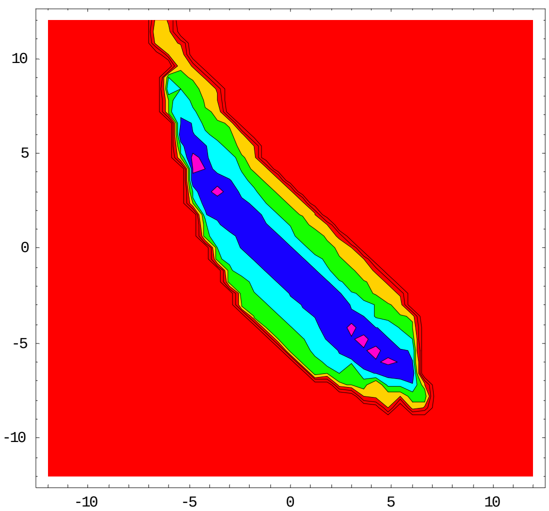
Variation on gradients for conventional CM's

Some more cases were studied in response to parameter exploration requests. These include:

5 hot CM at end of NL, first 3 NL zones run at 60, 50 & 50 MeV.



One hot CM at beginning, and 4 at end of NL.



South Linac

The case with South Linac is relatively unchallenging due to the much reduced momentum ration between top and bottom passes. Figure 5 shows an optimization of the beam envelopes for the last 4 passes in the South Linac with all 5 100 MeV CM's placed at the end[6]. Note there are no equivalent 1L00 and 1L01 quads to perform a scan search. The outcome nonetheless suggests this arrangement is quite comfortable for the South Linac.

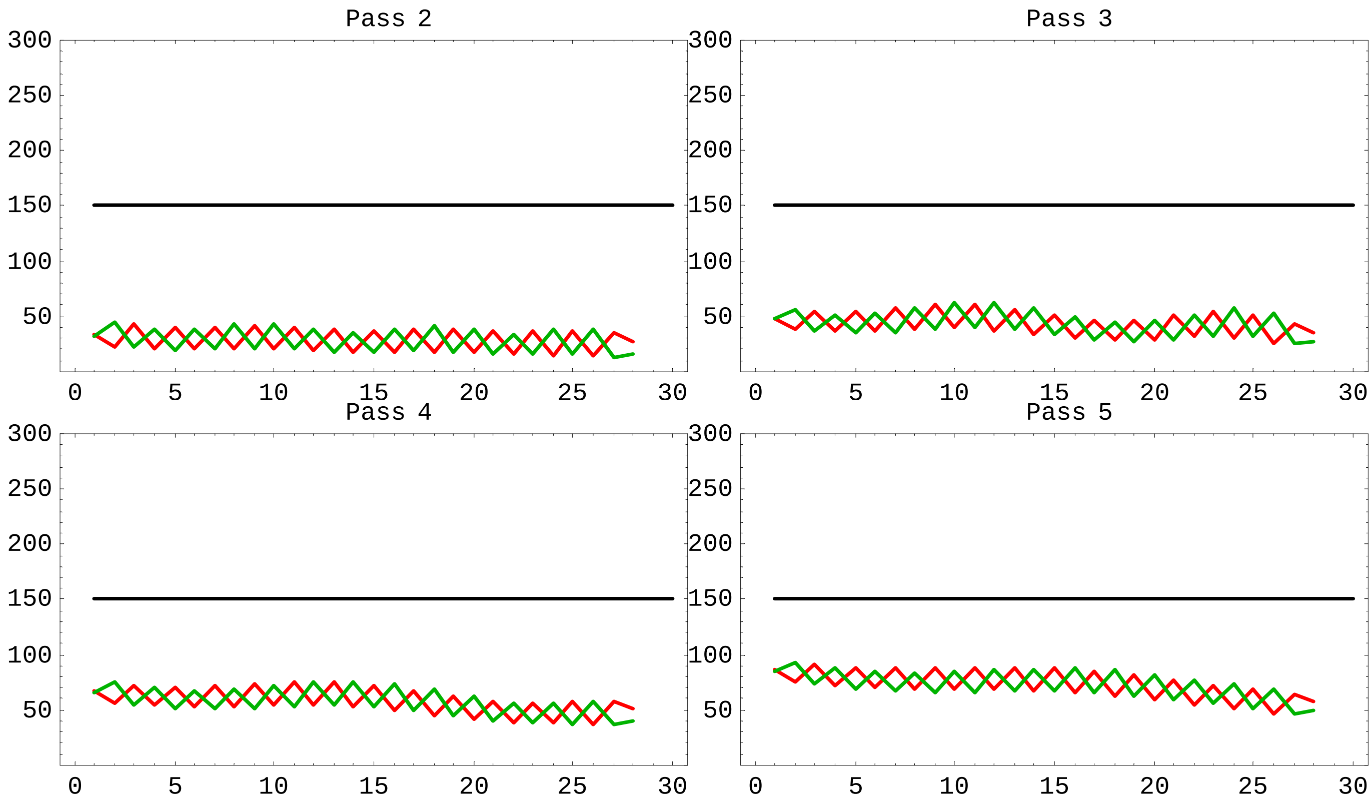


Figure 5. Optimized South Linac Beam Envelope (red: β_X; green: β_Y; in m) with all 5 Hot CM's at the End

[6] Only the linac proper is shown. Admittedly when extrapolated into Spreaders and Recombiners larger β will be seen in the dispersion suppressors, although not near the level of North Linac.

Impression So Far

Clearly ease of operation and optical stability can be gained by placing most, if not all of the 100 MeV cryo-modules at the front end of the North Linac. When they are all placed in the rear end, the optimization found only one solution in the entire scan of the quad strength space where global β is below 300 m. In reality it would be difficult to expect that we can count on this one solution to define the nominal optics. Therefore in this scenario one should expect overall peak β to be at the 350 m level, compared with 250 m or less in the opposite case.

Study of other scenarios suggests that visible improvements start to take shape with 2 hot CM's placed in the front. Depending on how other factors, including cost, feature in the final analysis, these alternate scenarios may prove preferable to the current baseline with all 5 hot CM's located at the end of North Linac.

References

More detail can be found at the following links.

NL Momentum Profile and Phase Advance Options for 12 GeV, Y. Chao October, 2004

12 GeV NL Configuration Options and Global Matching - Second Update, Y. Chao November, 2004