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Preliminary Design for the Recirculated Injector of CEBAF 12 GeV Upgrade

Overview

Projected upgrade of the CEBAF accelerator to maximal energy of 12 GeV (5.5 pass) requires upgrade in proportion of the energy delivered by the Injector, or roughly 123 MeV, up from 65 MeV under the current 6 GeV design. The solution adopted in the baseline upgrade design, where electron beam goes through two 30 MeV accelerating cryo-modules (CM) twice via recirculation to minimize cost, has been studied extensively. This note describes the outcome of this study.

Geometrical Layout

The entire recirculated injector complex from exit of the cryounit at 5 MeV to injection into the North Linac at 123 MeV is conceptually depicted in Figure 1, which also shows part of the new Arc 10 at the same vertical elevation. Figure 1a focuses on the detail of this complex by components in exact dimensions. This includes the following:

1. 5 MeV chicane into first pass cryo-modules (CM).
2. First pass CM's; top energy 64 MeV
3. Entrance into recirculator
4. Recirculating arcs consisting of 4 45° bends with extra edge focusing
5. Backleg matching sections
6. Path-length chicane providing up to ±1 cm control of path length with roughly ±3 cm horizontal excursion at the mid-point.
7. Reinjection into second pass CM
8. Second pass CM's; top energy 123 MeV
9. Extration from second pass CM
10. Intermediate matching for final North Linac injection
11. Injection chicane
12. Arc 10 at the same vertical elevation

This geometrical information is rendered[1] more realistically for congested areas in Figures 1b through 1e. The spatial constraints in the Injector part of the tunnel present very stringent conditions on the overall design. A few points are worth noting about this baseline geometry:

- The Injector recirculator spans most of the space currently comprising the aisle next to the Injector cryo-modules. It was possible to make all the optical components, namely dipoles and quadrupoles, clear the wall on the opposite end with acceptable optical transport. When realistic girders are introduced, the tunnel wall may need to be "shaved" by up to 3.24 cm at some locations.
- There will be intersection of the Injector recirculation line with Arc 10. Elements have been re-arranged to avoid collision. This can be seen from the detail of Figure 1d. Compromise made

[1] Courtesy Jacki Smith.

under this limitation may be mitigated by reversing the orientation of girders when more realistic installation planning takes place in the future.

- Alternate solution where the recirculation line is tilted at an angle to avoid Arc 10 has been studied, including skew quad implementation to counteract coupling effects. This has been abandoned due to its excessive complexity.

Transverse Optics

Figure 2 shows the lattice parameters of the entire Injector recirculation line from 5 MeV to the injection into North Linac at 123 MeV.

- Extra focusing required in the 180° arcs was made possible only through artificial pole-face angles in each of the eight 45° dipoles.
- An optimizing procedure has been invoked to obtain the 2-pass optics around the CM's at disparate energies using common quadrupoles. This has resulted in the apparently favorable beta functions in both planes for both passes. Sensitivity of this optical solution, as well as consequence of more realistic modeling of the CM's, will nonetheless need further investigation[2].
- The vertical beta function at the path-length chicane has also been minimized to avoid aperture problems.
- Overall tunability, especially that for betatron matching, appears to be adequate based on matching exercises performed so far.

Specs for dipoles and quadrupoles used are listed in Appendix A.

The Optim file for this design can be found at 12 GeV Injector Recirculation Optim Deck.

Longitudinal Dynamics

The complexity of the recirculated injector implies nontrivial longitudinal gymnastics for the beam. As the longitudinal beam characteristics entering the main accelerator are crucial to its global performance, the ability to optimize longitudinal behavior of the beam in the injector requires careful study. Some optimization has been carried out in an attempt to understand the degree of control available to achieve baseline longitudinal optics that produce desired bunch length at the entrance to North Linac. This includes the following premises.

- Input of ±0.25° bunch length and 9 keV momentum envelope width entering the current 1st cryo-module is assumed. This was used to back-propagate to the exit of the current quarter cryo-module to obtain starting configuration for the analysis.
- The M_{56} & T_{566} of the baseline components (various chicanes and recirculating arcs) are used. T_{566} are calculated by DIMAD instead of Optim.
- Time-of-flight contribution to M_{56} is included.
- The phase-slip between pass 1 and pass 2 is taken into account. This assumes that in pass 1 the 16 cavities are timed according to beam velocity such that the beam is on crest in all of them.

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[2] More realistic CM models have been measured recently. See Symplectified Transfer Matrices across Individual Cryo-Modules 02/03/05 (Chao). Evaluation of its consequence is currently carried out by Y. Zhang.

The different transit times between cavities in pass 2, from those in pass 1, then translate into cavity-dependent phase offsets for pass 2.

- Optimization is carried out to find the combination of the RF phase seen by the 1st pass beam, and the RF phase seen by the 2nd pass beam at the first cavity, that produces the smallest bunch length.

Figures 3 and 4 serve to demonstrate both the nominally achievable bunch length under the above premises, and more importantly what is possible with such an optimization scheme. In Figure 3 the nominal (±0.25°, ±9 keV) beam is maximally bunched at the exit of the Injection Chicane to about ±0.035°, with momentum spread of about 10^{-3}, by shifting the global first pass RF phase by 1.36° and the RF phase seen by the beam in second pass by 0.42° via the path length chicane[3]. The centroid momentum thus optimized is 123.237 MeV/C, with a slight asymmetry in the distribution around the centroid seen mainly due to distortion by RF and T_{566}. This bunching scheme may be overkill in reality and can be traded off in favor of smaller momentum spread if desired.

Figure 4 shows a study of an extreme cases where the initial bunch spread is 10 times larger, or ±2.5°. In this case it is nonetheless possible to find a phase combination to bunch it down to ±0.35° at the exit of the Injection Chicane, although more pronounced filamentation can be seen. These two examples serve to demonstrate the effect on longitudinal dynamics achievable through manipulating the RF phases in the recirculation process. A finalized baseline scheme, on the other hand, requires more careful study.

A related question concerns the sensitivity of the longitudinal dynamics. This is an ongoing topic of study.

[3] The small phase shifts needed are however only incidental, as optimization under varying initial conditions has resulted in phase shifts up to 5°.

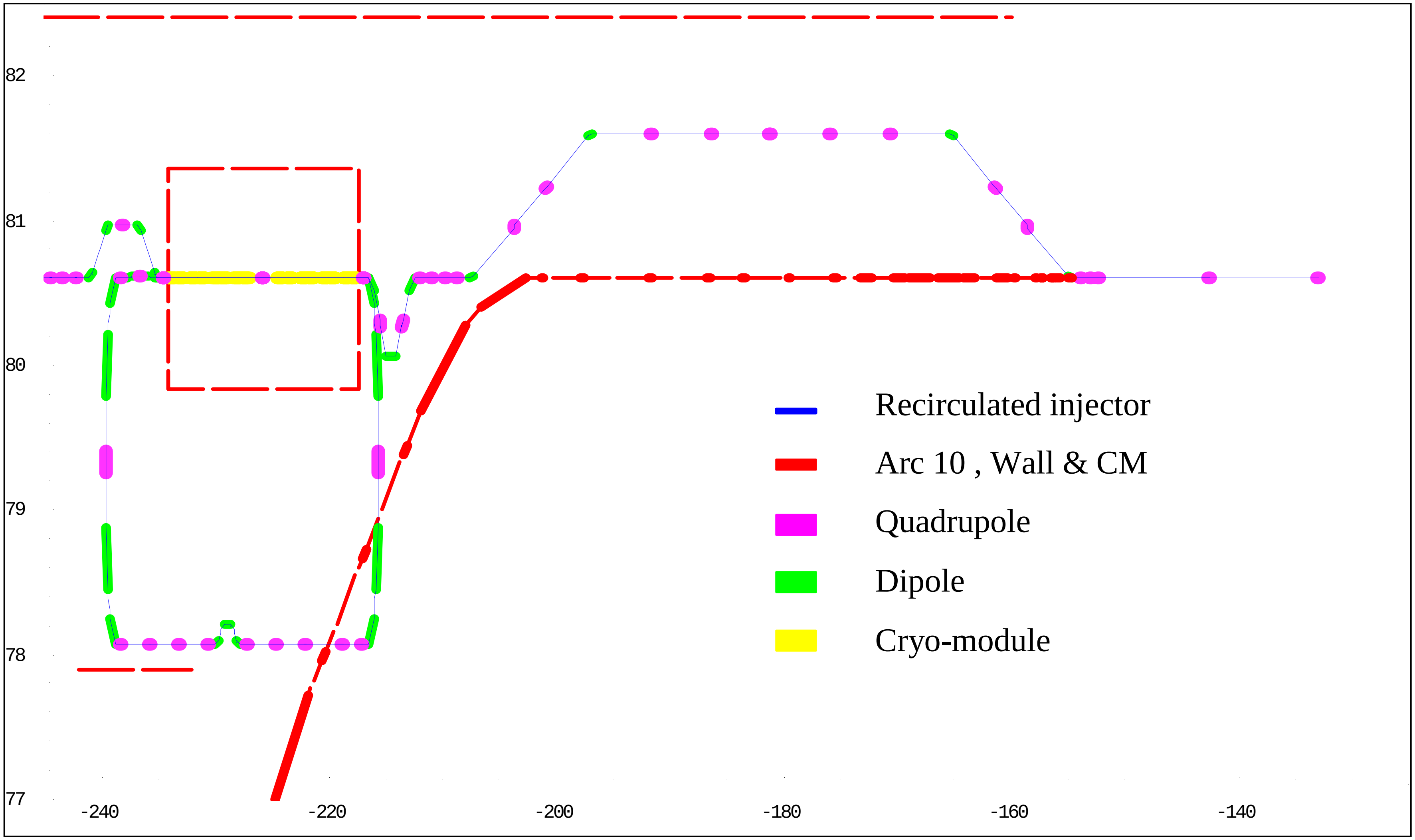

Figure 1.

Physical Layout of Injector Recirculation (Top View Global)

Realistic Quads, Inter-magnet & inter-line Separation

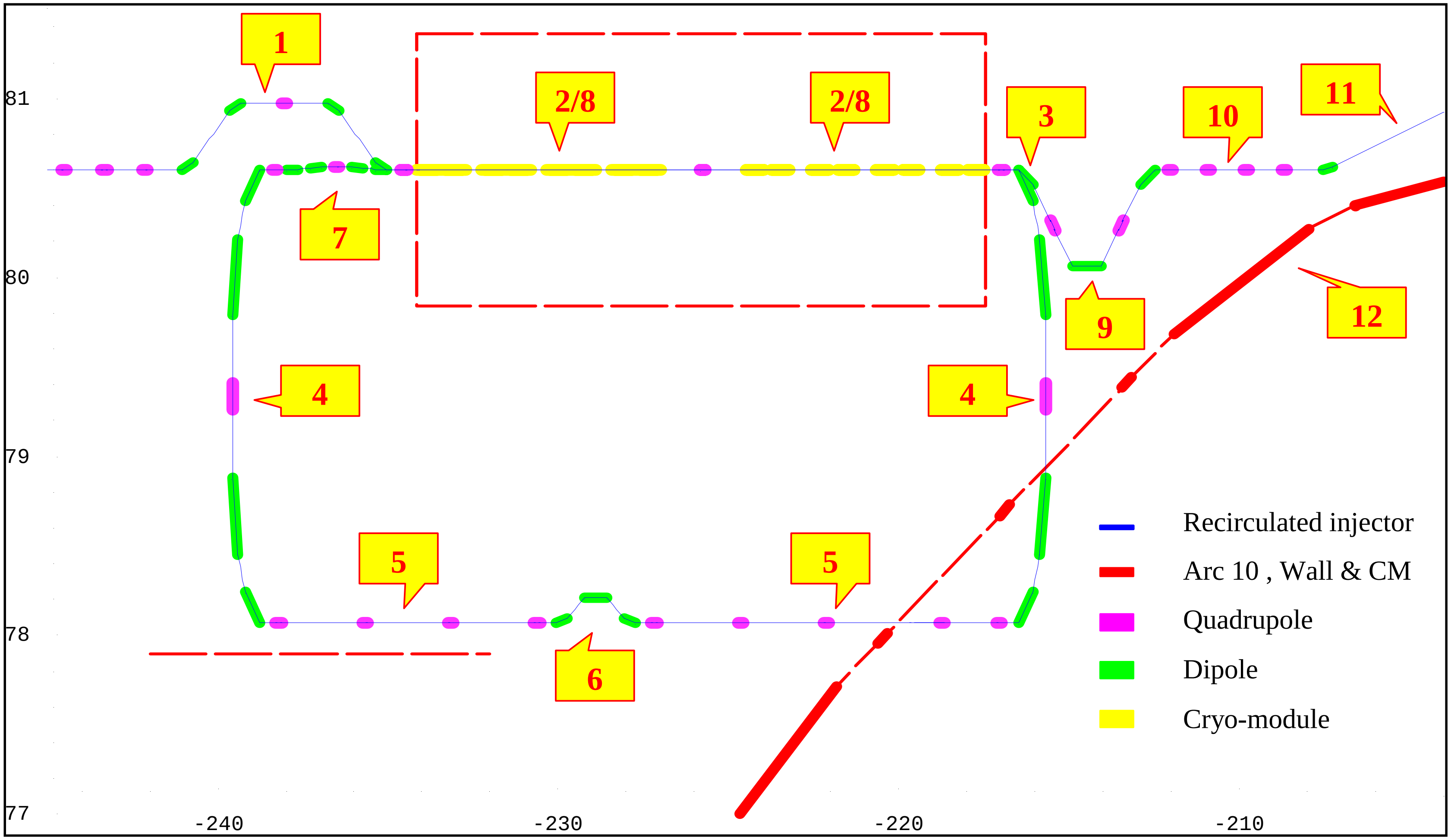

Figure 1a.
Physical Layout of Injector Recirculation (Top View Closeup)
Realistic Quads, Inter-magnet & inter-line Separation

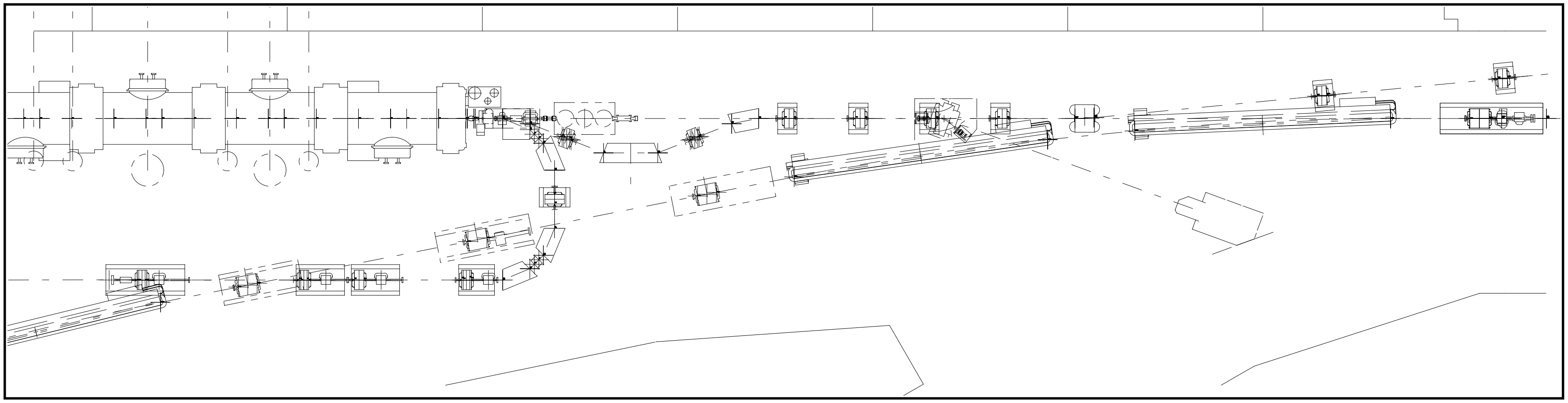

Figure 1b.
Overview of tight areas
(Dump line should be taken out in this drawing)

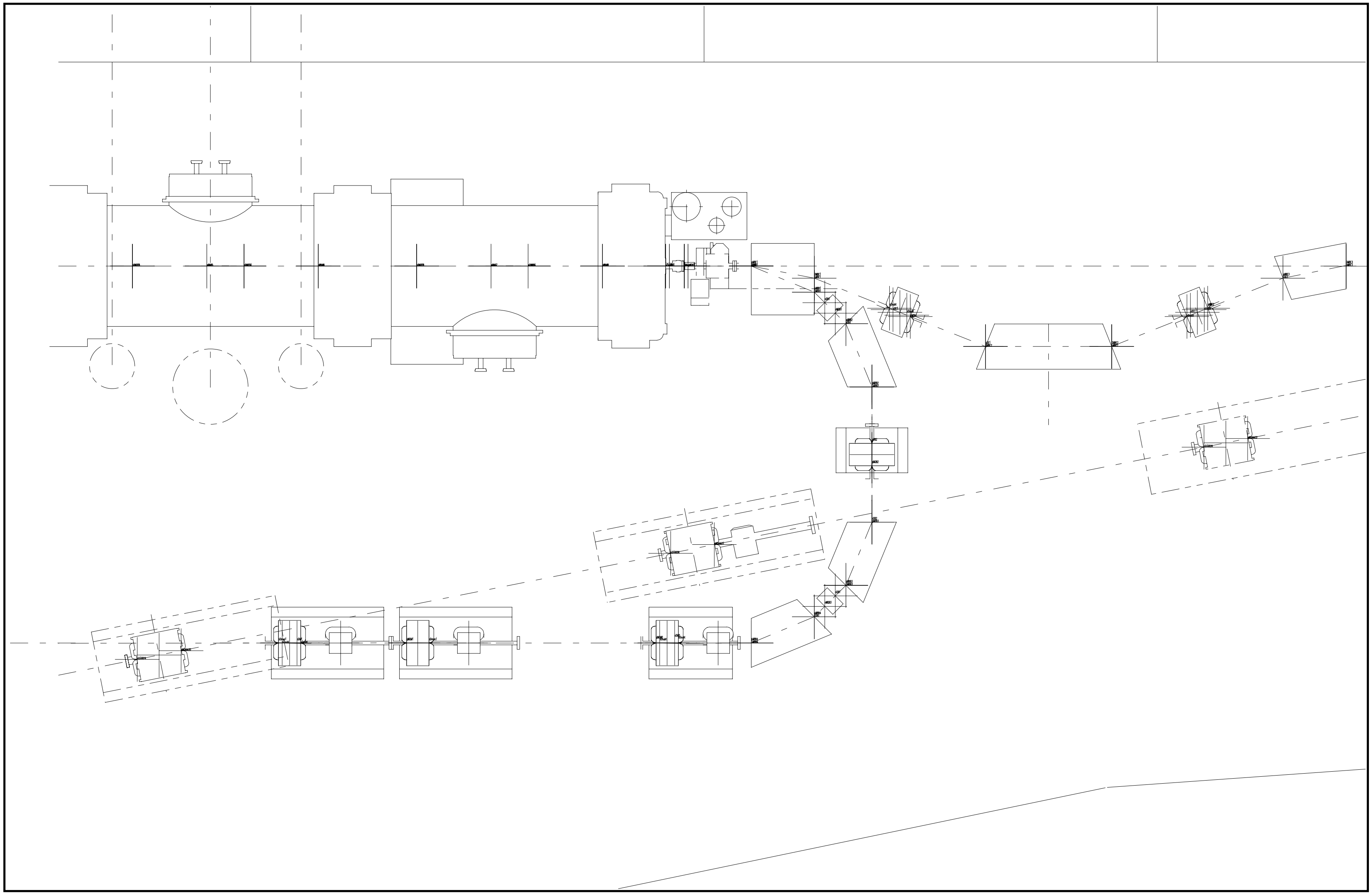

Figure 1c.
Close-up showing back-leg, Arc 10, and 2nd pass exit chicane

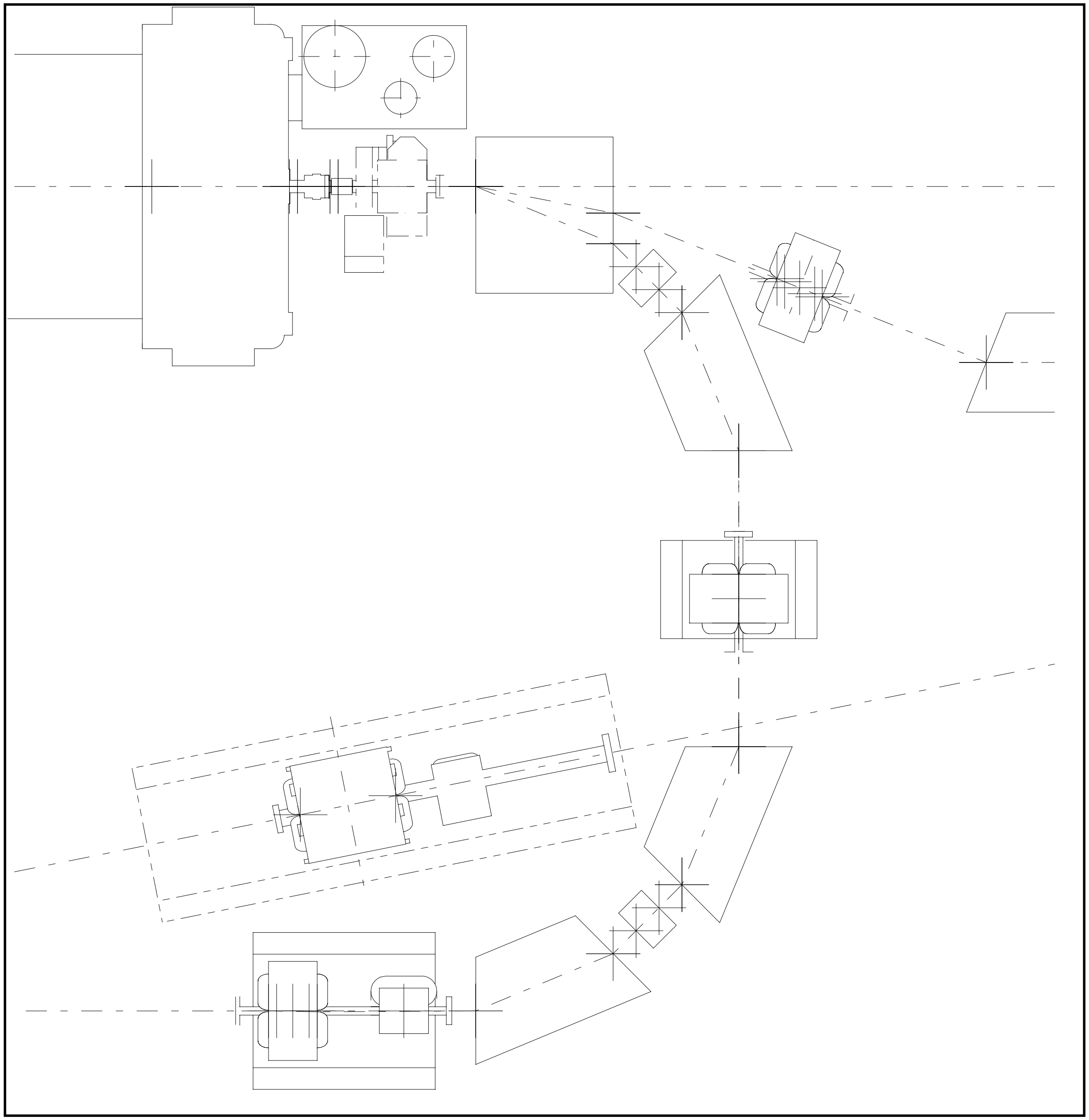

Figure 1d.
Further close-up of Figure 1c

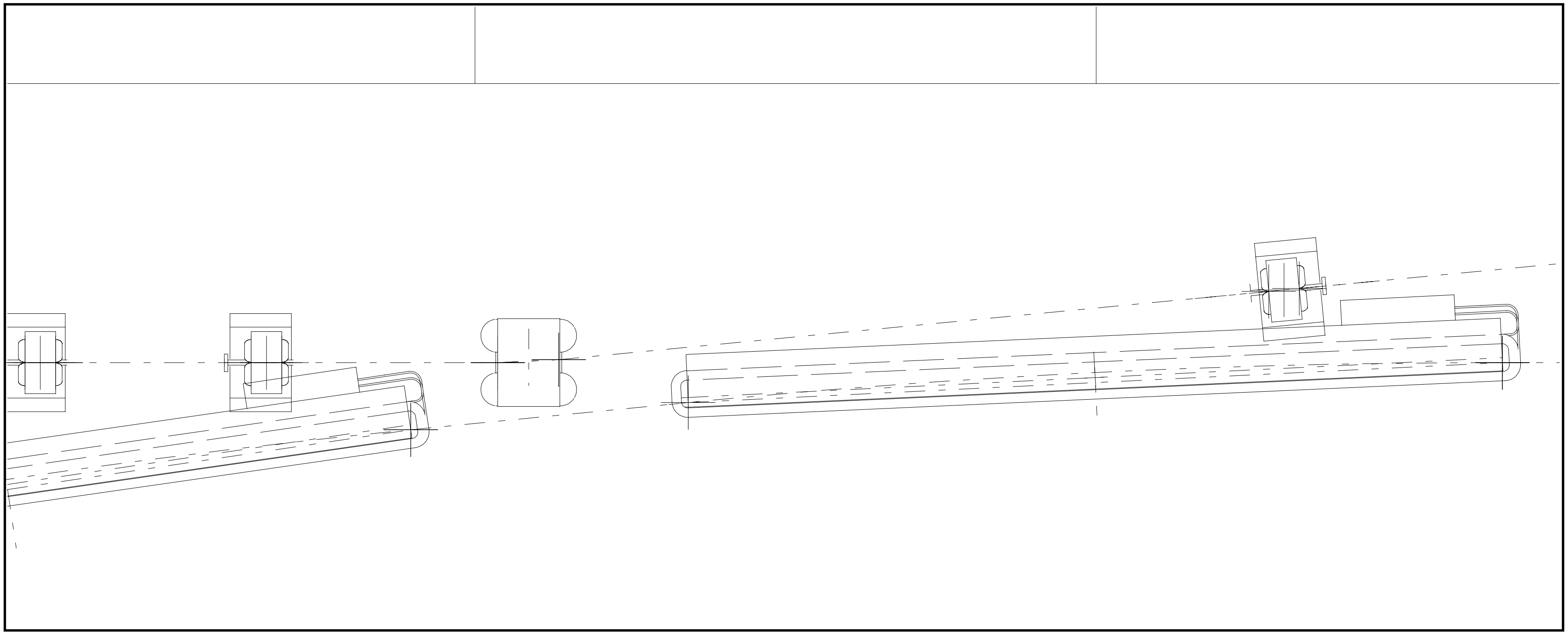

Figure 1e.
Close-up of Injection Chicane & Arc 10

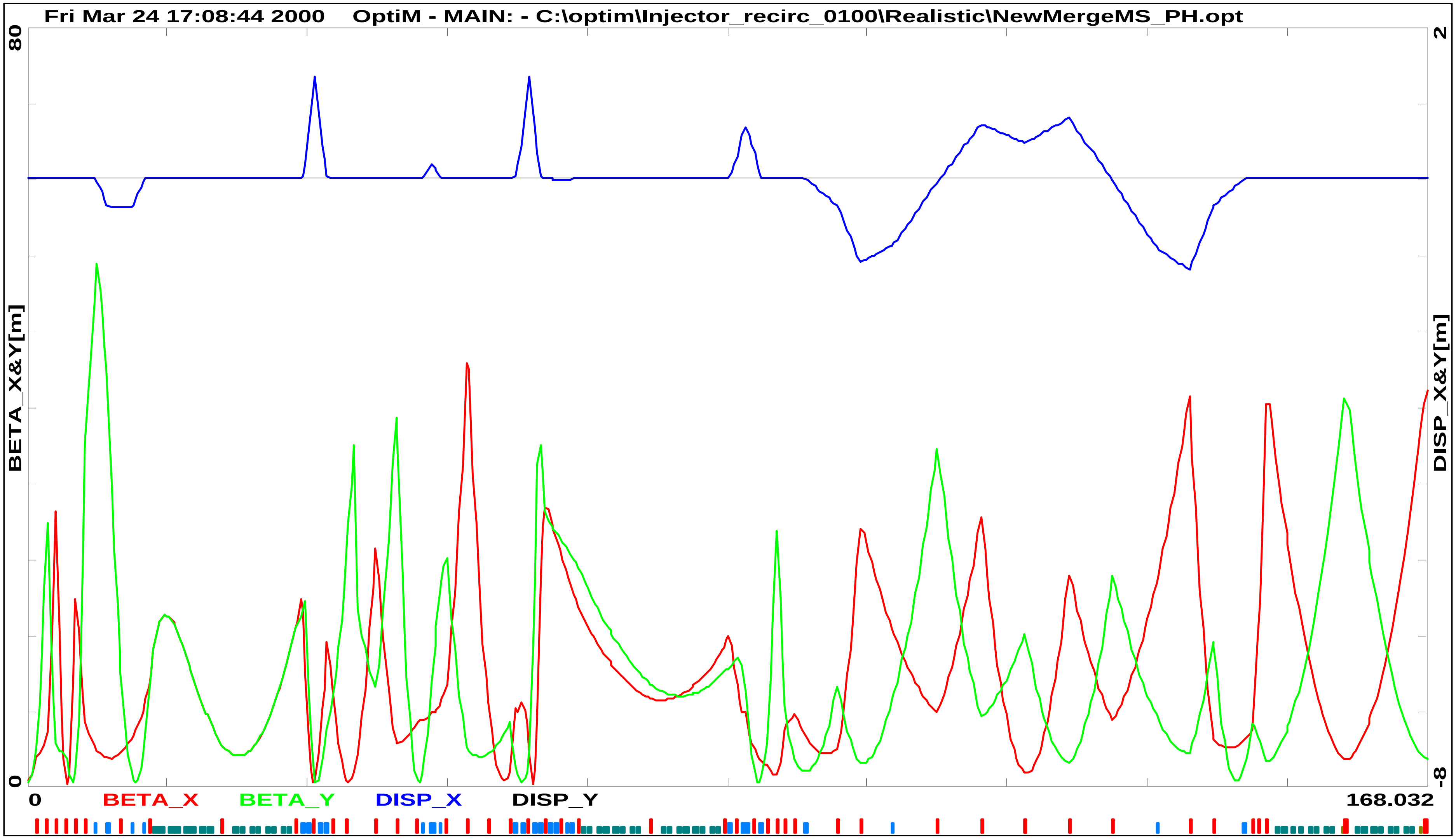

Figure 2.
Optics of Injector Recirculation (03/24/00)

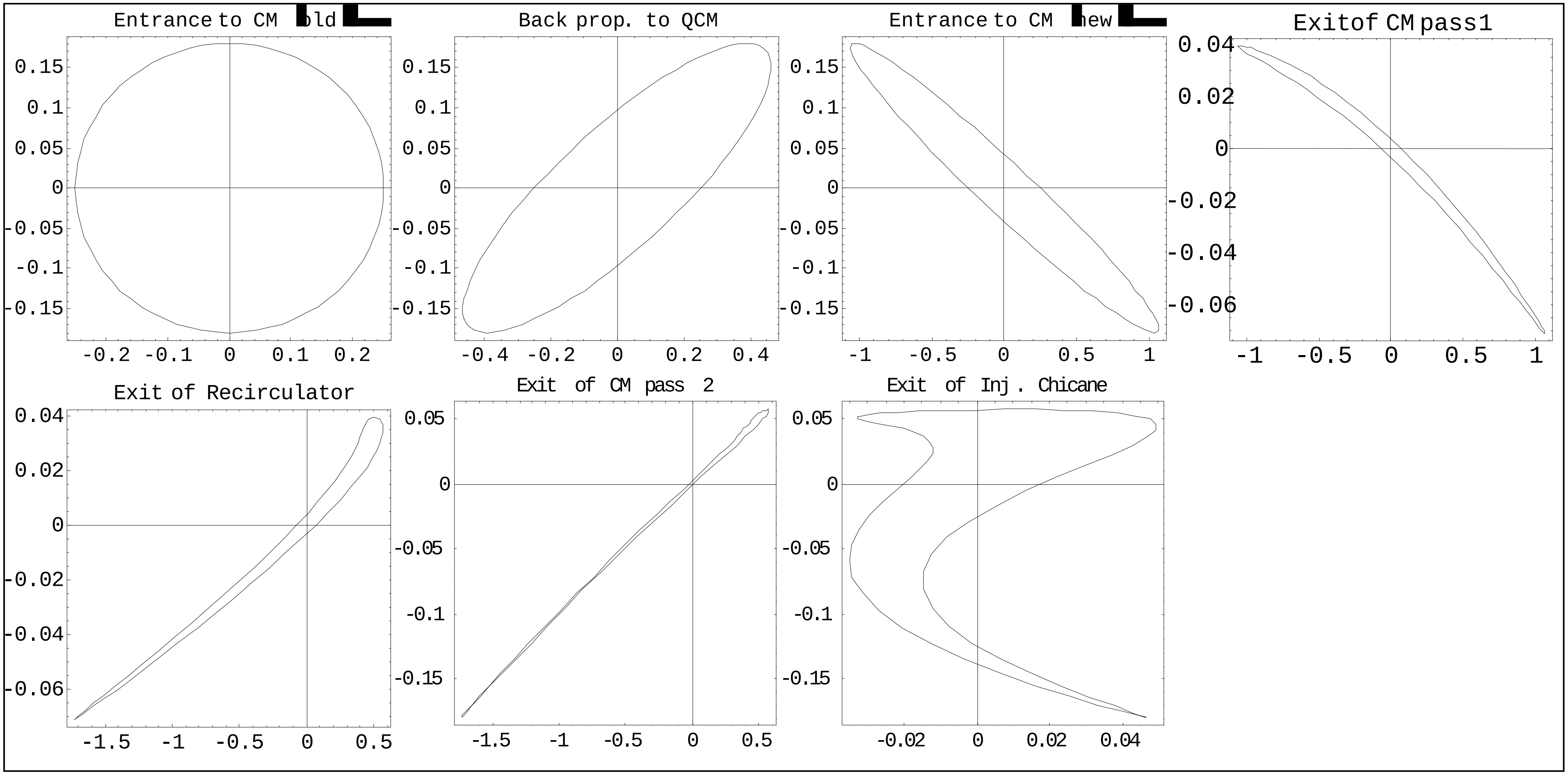

Figure 3. Longitudinal Envelope Based on
Back Propagation of Current 5 MeV Envelope (±0.25° by 9 keV bunch)
Phase Slip Effect Included for the 2nd Pass
Energy offset (%) vs. path length offset (RF °)
T566 effects included
Initial σ^{56} = 2.6×10^{-4} m
Pass 1 RF phase offset = 1.36°
Pass 2 RF phase offset = 0.42°

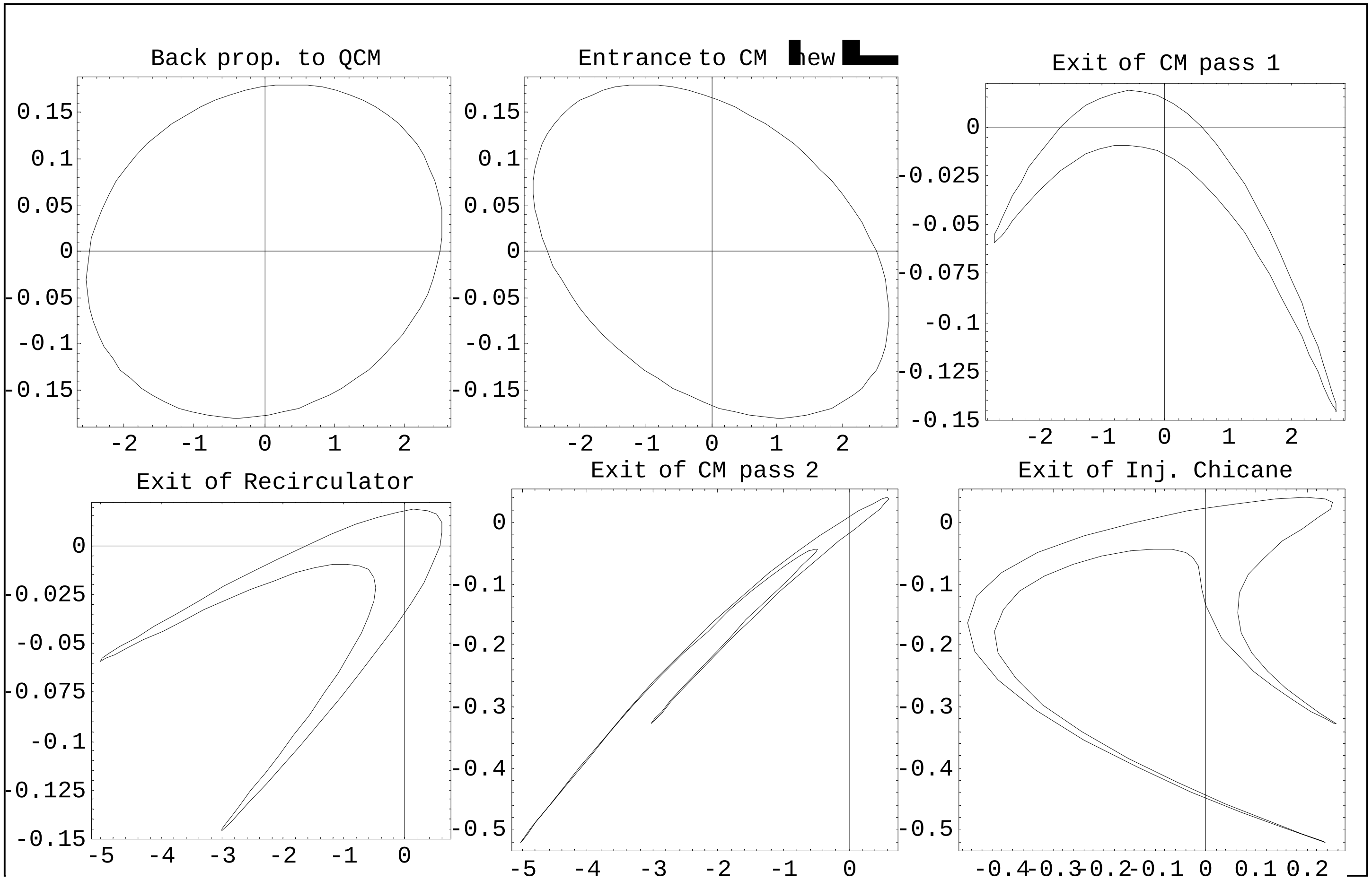

Figure 4. Longitudinal Envelope
Based on ±2.5° by 9 keV bunch
Energy offset (%) vs. path length offset (RF °)
T566 effects included
Initial $\sigma^{56} = 2.6\times10^{-4}$ m
Pass 1 RF phase offset = 0.5°
Pass 2 RF phase offset = -4.22°

Appendix A. Recirculated Injector Magnet Specs

Dipoles:

Name	L[cm]	B[kG]	BendAng[deg]
MBA1	31.4159	-0.151867	-15
MBA2	31.4159	0.151867	15
MBA3	31.4159	0.151867	15
MBA4*	31.4159	-0.151867	-15
MBB1+	47.1239	3.585	45
MBB2	47.1239	3.585	45
MBB3	47.1239	3.585	45
MBB4	47.1239	3.585	45
MBC1	42.0721	1.82243	20.4234
MBC2†	84.1441	-1.82243	-40.8468
MBC3	42.0721	1.82243	20.4234
MBC1	31.4159	1.43399	12
MBC2	62.8319	-1.43399	-24
MBC3	31.4159	1.43399	12
MBB5	47.1239	3.585	45
MBB6	47.1239	3.585	45
MBB7	47.1239	3.585	45
MBB8	47.1239	3.585	45
MBD1	31.0608	-0.151867	-1.25648
MBD2	31.0608	0.151867	1.25648
MBD3	31.0608	0.151867	1.25648
MBD4*	31.0608	-0.151867	-1.25648
MBE1+	43.4629	3. 585	21.7511
MBE2	86.9258	-3. 585	-43.5022
MBE3	43.4629	3. 585	21.7511
MBL0R01	30	-1.31331	-5.5
MBL0R02	30	1.31331	5.5
MBL0R03	30	1.31331	5.5
MBL0R04	30	-1.31331	-5.5

* These 2 are the same dipole for pass 1 & pass 2 beams.
+ These 2 are the same dipole for pass 1 & pass 2 beams.
† Beam excursion up to ±3 cm at center point is possible.

All dipoles are parallel-faced, except the 8 recirculation arc dipoles MBB1-MBB8, which have a 11.25° edge angle on each face.

Quads:

Name	L[cm]	G[kG/cm]
MQZ1	15	0.00749404
MQZ2	15	-0.0136254
MQZ3	15	0.0168137
MQZ4	15	-0.0170375
MQZ5	15	0.0162344
MQZ6	15	-0.00681597
MQA3	15	0.000290166
MQA5	15	-0.00228648
MQJ0L05	15	0
MQX1	15	-0.00758759
MQB2	15	0.248813
MQM0	15	0.0166053
MQM1	15	-0.051239
MQM2	15	0.0788873
MQM3	15	-0.0826603
MQM31	15	0.0126478
MQC3	15	-0.0529505
MQM4	15	0.0639271
MQM5	15	-0.00219764
MQM6	15	-0.112789
MQB5	15	0.248813
MQD1	15	0.0222735
MQD3	15	4.92507e-05
MQE1	15	-0.029694
MQE2	15	-0.00881594
MQIC1	15	0.108572
MQIC2	15	-0.274307
MQIC3	15	0.137625
MQIC4	15	0.0646911
MQD0R01	15	-0.126395
MQD0R02	15	0.0807008
MQD0R03	15	-0.0566854
MQMC1	15	0.0741118
MQD0R04	15	-0.0644395
MQMC2	15	0.0764092
MQD0R05	15	-0.0660587
MQD0R06	15	0.0847067
MQD0R07	15	-0.151408
MQMatch1	15	-0.194316
MQMatch2	15	-0.0442425