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E Linac EMBT-EABT-EHAT Phase One Major Components and Layout

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History of Changes

Release Number	Date	Description of Changes	Author(s)
1	Oct. 30, 2012	Initial Release	Y. Chao
2	Dec. 18, 2012	Minor optics and diagnostics placement refinements	Y. Chao
3	Mar 18, 2013	EMBT:Q5B name change 2767 G KdL for EHAT:Q1/Q2	Y. Chao
4	Apr. 24, 2013	Added EHAT:ACCT2 & EHAT:FC4	Y. Chao
5	Jan. 17, 2014	EMBD elements moved downstream (32 cm) Added EMBD Dump and extra drift for shielding EABD elements moved downstream (43 cm) EHAT:Q3/Q4 are now bipolar.	Y. Chao
6	Jun. 16, 2014	Relocation/Removal of wire scanners Removal of EHAT:RFSH4 Finalized EMBD and EABD layout Added EMBD operating optics	Y. Chao

1 Abstract

Design of the E Linac beam line sections EMBT, EMBD, EABT, EABD and EHAT are described. This document consists of the following

- Design goal
- Requirements and constraints
- Implementation
- Overall geometry
- Design detail, strategy, and performance assessment
- Element specs
- Element coordinates

This document pertains to the Phase One mode of E Linac in which a single pass electron beam at nominal energy 10 MeV is transported through the sections described.

This note is organized as follows

Sect. 2	Overview and Design Goal
Sect. 3	Requirements and Constraints
Sect. 4	Implementation and Overall Geometry
Sect. 5	Optics Design Detail
Sect. 6	Evaluation of Configuration Performance
Sect. 7	Element Specifications
Sect. 8	Element Coordinate Table
Sect. 9	References
Appnd. 1	Rules for Position Tweaking

2 Introduction

This note defines the design, in the scope of E Linac Phase One, from the injector cryo-module (EINJ) exit to the last dipole of EHAT, EHAT:MB4. This comprises the following sections: EMBT, EACA, EABT, EACB, and EHAT, branching at various locations into spectrometer lines EMBD and EABD. Major components forming EMBT, EMBD, EABT, EABD and EHAT, at nominal energy from 10 MeV to 30 MeV, will be described.

Design requirements for this section of the E Linac may be best illustrated with a discussion of its function below.

2.1 Purpose

The main purpose for this section of the E Linac is to transport and accelerate the 16 pC/bunch photo-fission beam from the upstream EINJ section at 10 MeV to the downstream EHBT section at 30 MeV. After the 10 MeV ELBT- EINJ [1][1,2] the beam enters the EMBT and is transported into the main linac consisting of accelerating cryo-modules (ACM), named EACA and EACB, and an EABT section between the 2 ACM's. In phase one only EACA will contain an ACM, and EACB will be a drift. This is followed by EHAT, a beam

[1] E Linac Major Components and Layout up to Exit of Injector Cryo-Module, TRI-DN-10-08

transport section in phase one that will also be responsible for two-pass beam separation in phase 3. The beam destined for photo-fission targets leaves EHAT and is directed to downstream EHBT[3]. The electron beam can also be diverted into spectrometer lines EMBD (from EMBT) and EABD (from EABT) at branching points for diagnosis and tune up.

Beam properties are listed below.

Nominal Kinetic Energy EMBT (MeV)	10
Nominal Kinetic Energy EABT-EHAT (MeV)	30
RMS ε_z (keV-ps)	<20
Normalized RMS ε_x (μm)	≈ 6
RMS Momentum spread (%)	≤ 0.2 (at 10 MeV)
RMS bunch length	$\sigma_z \leq 0.2$ mm

2.2 Scope

The three phases of E Linac implementation are, for the purpose of this note only,

1. One acceleration cryomodule (EACA) only, with a simple 2-bend chicane in EMBT
2. Two acceleration cryomodules (EACA & EACB)
3. Recirculation loop included with a 3-bend merger in EMBT

Beam line sections EMBT, EMBD, EABT, EABD and EHAT for Phase One operation are covered in the current document.

2.3 Definitions and Abbreviations

- Coordinate system: The Cartesian coordinate system defined herein is such that the origin is in the centre of cyclotron, +x points to East, +y points to North, and +z points upward.

3 Requirements and Constraints

3.1 Top Level Requirements

- The beam line sections described in this document shall effect electron beam transport between respective start/end points indicated below
  - EMBT: From valve (not inc.) EINJ:IV1 to valve (not. Inc.) EACA:IV0.
  - EMBD: From dipole EMBD:MB0 to end of EMBD dump.
  - EABT: From valve (not inc.) EACA:IV2 to (inc.) EABT:BPM3
  - EABD: From dipole EABD:MB0 to end of EABD dump.
  - EHAT: From (inc.) EHAT:XY0 to (inc.) EHAT:MB4
- The electron beam kinetic energy ranges designed for beam line sections described in this document are[2]
  - EMBT before EMBT:MB5C: 7 MeV to 15 MeV

[2] High end numbers correspond to capability required in future phases. However current design is made to meet this future capability, mainly in the area of magnet range, so that magnet upgrade is not required in future phases. Ability to transport lower energy beam in nominally higher energy sections is retained for diagnostic and tune-up possibilities.

  - EMBT from exit of EMBT:MB5C to valve EACA:IV0: 7 MeV to 47 MeV
  - EABT: 27 MeV to 45 MeV (Low end extends to 7 MeV if beam is transported with EACA off)
  - EHAT: 27 MeV to 75 MeV (Low end extends to 7 MeV if beam is transported with EACA off)
- The maximum electron beam current transported in beam line sections described in this document is 10 mA.

3.2 General Requirements

- Simple and robust.
- Low loss.
- Easy to tune.
- Easy to maintain.
- Within CFI budget and schedule.

3.3 Specific Requirements

- Shall be capable to transport electrons with loss less than 10^{-5}/meter [4].
- Shall keep transverse beam size (RMS) below 2 mm.
- Shall keep overall emittance growth below 0.5%.
- Shall keep beam trajectory magnitude after orbit correction to less than ±1 mm (at 99.9% probability cutoff), in order to accommodate inherent betatron and dispersive beam sizes, ambient field effects, and head room for tuning and beam based diagnosis.

3.4 General Constraints

- The layout shall fit within the e-hall building civil construction footprint. This resulted in the specific constraints described below after global effort was made in fitting all necessary beam line components and service/support equipments inside the e Hall floor plan.
- Shall stay within CFI budget and schedule: where possible, magnet types shall be rationalized and minimized.

3.5 Specific Constraints

- All beam line sections described in this document are at the level Z=-0.6096 m in the global Cartesian frame (centered at the Cyclotron).
- Cryomodule-containing sections EINJ, EACA and EACB, and associated SRF and cryogenic service components will not be relocated in future phases. This requires existence proof and adequate feasibility studies of solutions for future modes of operation compatible with current (phase one) layout. This includes the RLA mode with energy doubling in second pass and the ERL mode with energy recovery in second pass, both requiring beam separation in EHAT and recombination in EMBT.
- EMBT shall match the optical parameters at the exit of ELBT at location
  - x=−34.9930 m
  - y=-7.4878 m
  - z =−0.6096 m

with beam pointing in direction

  - 36° West (of the +Y axis)
  - True horizontal

as defined in the global Cartesian frame centered at the Cyclotron.

- The beam condition at ELBT exit as input to the design is
  - Nominal kinetic energy: 10 MeV
  - $\beta_X = \beta_Y = 5$ m
  - $\alpha_X = \alpha_Y = 0.40$
  - Normalized RMS emittance in X & Y planes: 5μm
  - No dispersion in X and Y
  - RMS $\delta P/P = 2\times10^{-3}$
- It is assumed that quadrupole maximum allowed insertion length shall be 15.0 cm for the sections described in this note [5].
- It is assumed that dipole maximum allowed insertion length shall be 22.0 cm [6]
- The section EACA consists of the first ACM with total length 3.825 m. This is the length of the cryomodule box wall-to-wall. The insertion length in the beam line is 3.512 m cold mass valve to cold mass valve. However, all optical and diagnostic elements, except specifically designated BPM's and correctors, have to be placed outside the region occupied by the 3.825 m wall-to-wall length due to ACM geometry [7].
- The insertion length of the DCCT (DC current transformer) shall be no more than 40 cm.

3.6 Implied Requirements on Other Systems

- A preliminary recommended sextupole component tolerance for EMBT chicane dipoles is $K_S \leq 3.5\ m^{-2}$ [8], where the kick δX' received by beam with offset δX due to the sextupole component is

$$\delta X' = K_S\ (\delta X)^2$$

It has been shown [9, 10] that for the tolerance specified above total sextupole contribution to emittance growth from the EMBT dipoles is well below 0.5%.

- Suppression of ambient magnetic field by mu-metal shielding and active electric current carrying wires around the EMBT-EABT area shall achieve DC field level below 0.2 G [11] under all circumstances of cyclotron operation and equipment configuration over the footprint of EMBT-EABT-EHAT. This criterion is a prerequisite for achieving beam orbit envelope specs discussed in the current note [12].

- The following tolerance specs are required to meet beam orbit envelope specs discussed below [12].

  \- Alignment error tolerances, in both position and angle, in the transverse dimensions (namely, left-right and up-down while looking down the beam line) are given as follows. <u>All quantities are given in terms of RMS</u>.
  - Transverse (up-down and left-right) alignment error of <u>all magnetic elements</u>: 150 μm
  - Angle (pitch & yaw) alignment error of dipoles: 150 μm divided by dipole length
  - Angle (roll) alignment error of dipoles: 200 μrad

  \- Alignment error of RF cavities in EACA, although not part of the current document, must be included in the orbit envelope analysis[3].
  - Transverse (up-down and left-right) alignment error of all RF cavities: 400 μm
  - Angle (pitch & yaw) alignment error of cavities: 400 μm divided by cavity length

[3] Implementation detail of this alignment accuracy depends on cryomodule design and implementation detail and will not be discussed here. It was nonetheless provided during ELBT design as an achievable number by SRF group.

- Dipole excitation error[4] (RMS) - Fraction of excitation: 2×10^{-4}
- Variation in residual ambient magnetic field: 0.2 Gauss
- BPM mechanical offset error: 150 μm

- For alignment of components in the beam line according to the finalized element positions[5]:
  The following longitudinal range of variation beyond achievable alignment accuracy is allowed during installation. This level of control is required to preserve optical tunability. All quantities are given in terms of "maximum allowed" (not RMS).
  - Allowed longitudinal range of variation from design position for quadrupoles: ± 2 mm
  - It is required that any deviation from the design longitudinal position of quadrupoles beyond standard alignment tolerance of 150 μm, even if within the values given above, be communicated to the Design Office to facilitate updating of related database.

- All dipoles are required to be placed with standard achievable tolerance of 150 μm RMS in longitudinal position[6]. In other words, there is no allowed range of variation beyond alignment accuracy. Transverse position and angle tolerances are as given in the previous paragraph.

All other elements should be placed with allowed range of variation specified in the table [13] for diagnostic elements and correctors.

4 Implementation and Overall Layout

4.1 Compatibility with Future Operation Modes and Installation Phases

Beam line layout for phase one EMBT-EABT-EHAT has been demonstrated to be compatible with future RLA and ERL modes by explicit construction and optics design [12, 14]. This includes cryomodule placement and associated service components.
Hardware elements required for future phases but not phase one will be explicitly noted where applicable in this note. They are relevant to phase one installation due to potential space allocation and diagnostics box design needs.

4.2 Residual Orbit Envelope

The requirement on residual orbit magnitude can be satisfied if the error tolerances described in 1.6 can be met given the element configuration to be discussed below.
The configuration of orbit monitoring and correction elements has undergone detailed analysis to ensure absence of blind spots and degeneracy. It has been demonstrated that [12] application of standard orbit correction procedure will keep the residual orbit envelope within spec. This will be discussed in the following.

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[4] This is not the error in field strength with respect to design, but rather the residual error after adjusting the dipole excitation with beam based methods. Since this is a "same-spot" correction, achieving error tolerance of this order should not be too difficult if allowed by power supply resolution. Alternatively this should be used for dipole current stability tolerance as well since the effect is the same.

[5] The values cited here only apply to placing elements physically and field validation of coordinates by the alignment group. They are not intended as guideline for Design Office in laying out elements in the design drawing, for which one is referred to Section 8.

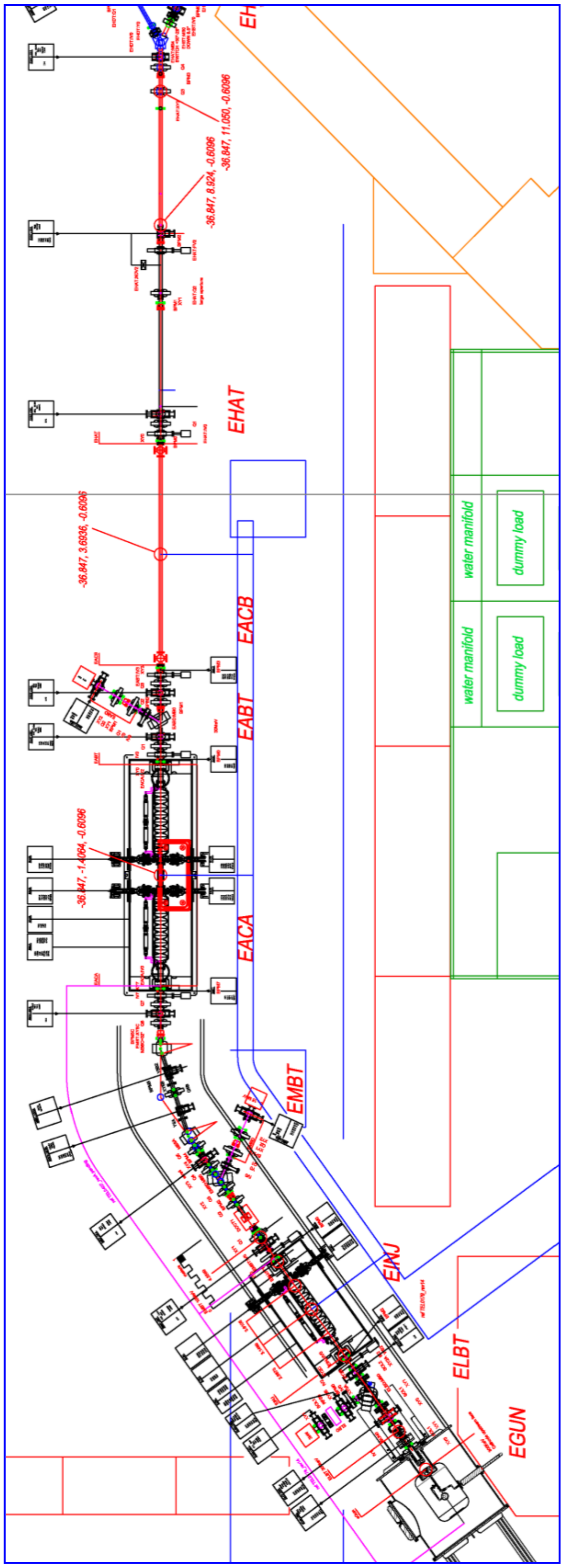
[6] Detail on exact procedure to follow to assure this alignment accuracy for dipoles, such as application of external alignment monuments, depends on the final dipole design and implementation procedure, and is not discussed here.

4.3 Easy to Tune

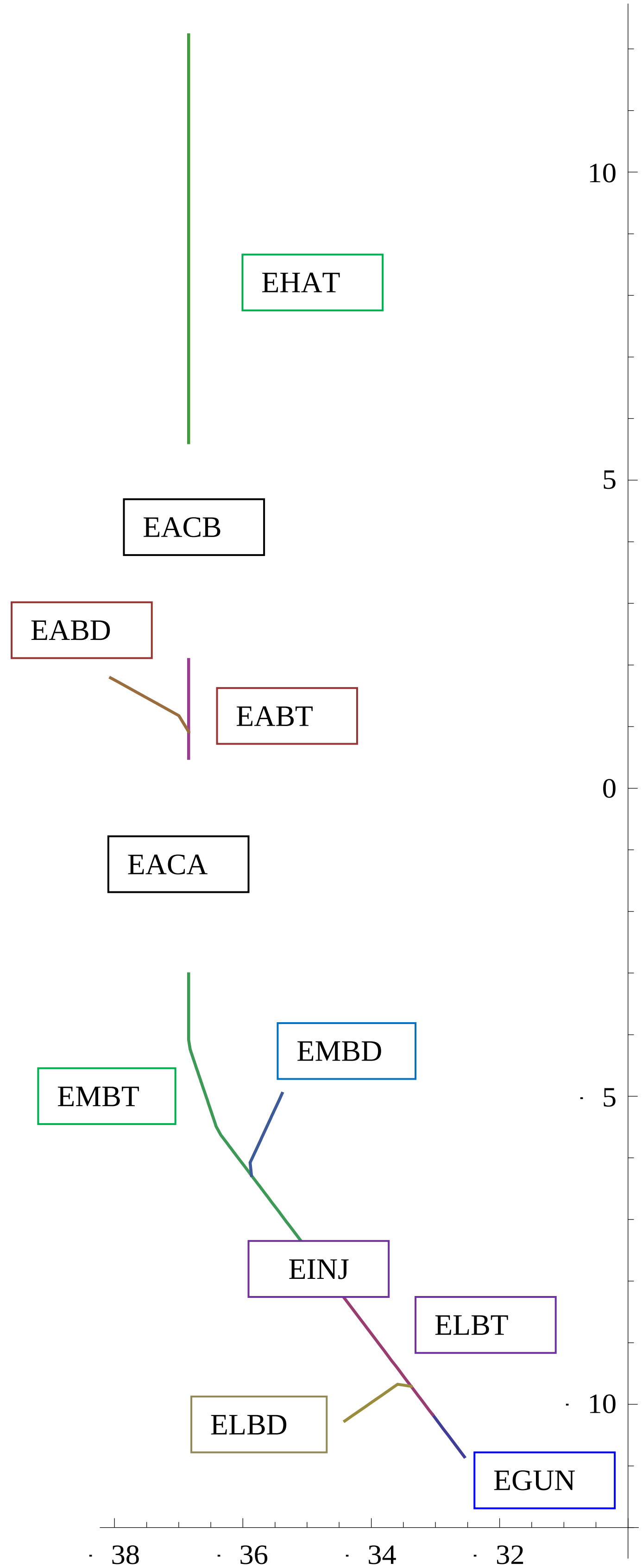
For phase one, adequate optics matching capability is provided in EMBT, receiving beam out of the EINJ, and in EABT-EHAT, receiving beam out of the EACA. Ability of these two consecutive matching sections to deliver exactly matched beam into EHBT has been demonstrated over a wide range of input conditions.
Diagnostic elements required to verify matching have been included at strategic locations with identified operation procedures.
Spectrometer lines (EMBD and EABD) have been designed with diagnostic and control elements to facilitate RF set up and diagnosis of longitudinal phase space.
For phase one a quadrupole is provided in EMBT to achieve suppressed dispersion into the main linac (EACA-EABT).

4.4 Overall Layout

Figure 4.1 shows plan view of phase one e-linac section inside the e-hall from EGUN to EHAT. Individual sections covered in this note will be described in further detail in subsequent sections.



EHAT
EACB
EABT
EACA
EMBT
EINJ
ELBT
EGUN
water manifold
dummy load
water manifold
dummy load



EHAT
EACB
EABD
EABT
EACA
EMBD
EMBT
EINJ
ELBT
ELBD
EGUN
10
5
0
5
10
38
36
34
32

Figure 4.1. Left: E Linac section in the e Hall from EGUN to EHAT with detail of elements. Right: Concept of segmentation of the same section in cyclotron center coordinates (meters).

5 Design Details by Section

5.1 EMBT and EMBD

Overview

EMBT and EMBD are sections responsible for multiple functions. For phase one these include

- Matching beam out of EINJ into the main linac starting at EACA
- Setting up RF parameters of EINJ and characterizing longitudinal beam properties (done in EMBD)
- Improving longitudinal beam phase space characteristic into EACA through collimation
- Performing unique diagnosis such as non-invasive high beam current monitoring (DCCT) and energy fluctuation monitoring.

In phase one, EMBT consists of a straight section after EINJ containing 5 matching quads, corrector magnets, and diagnostic elements. This is followed by a 2-bend chicane each with 18° of bend angle. In future phases this section is responsible for combining the injected beam with the recirculated beam into the main linac. In phase one its main function is to cause the entire assembly to conform to the baseline geometry. Dispersion arising from this chicane is suppressed through a quadruple. BPM and screen located near the high dispersion point ($\eta_X \approx 20$ cm) are expected to serve as diagnostics for momentum offset related beam properties. This is also the place for the collimation system, where a collimating jaw is employed to remove low momentum tails before the beam enters the main linac. There is a beam-shaping quad doublet after the chicane for fine adjustment and later matching.

EMBD consists of a 60° bend to branch the beam into subsequent spectrometer line with steering and focusing magnets, diagnostics and a 3kW Faraday cup in the dump. More detail of the diagnostics will be given in the section to follow.

Optics of EMBT

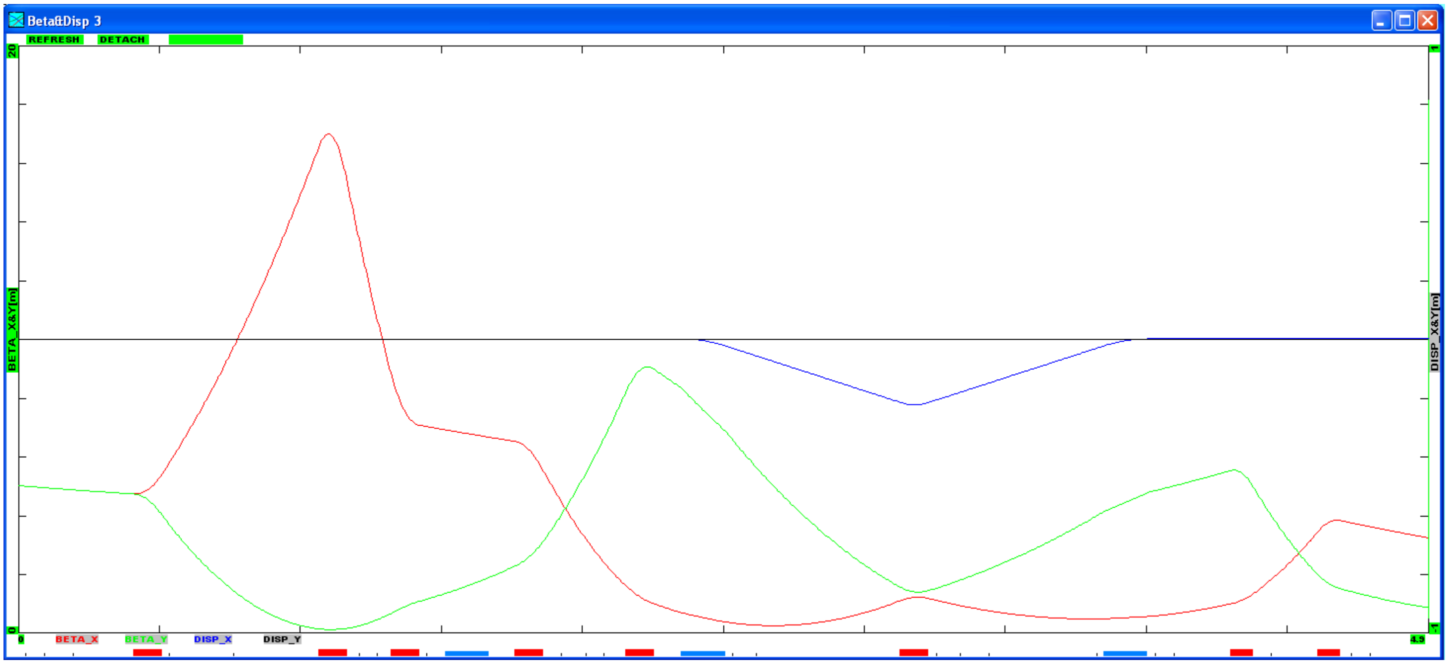


Figure 5.1 Optics of EMBT showing β_X (red), β_Y (green), η_X (blue). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-20 m for β_{XY} and -1m to +1 m for η_X.

The multipole content of the two rectangular bending dipoles sampled by beam is much reduced if the dipoles are symmetrically placed, namely, symmetric with respect to the entry and exit orbits. This is the adopted configuration. The need to match to this configuration led to the β_{XY} pattern upstream as shown. While this beam profile is not a concern as the peak value is still within spec, this is larger than the case where the dipoles are not symmetrically placed. It should be noted that without 5 matching quads here it would be much more difficult to keep the beam envelope within spec.

Configuration of BPM, corrector and other diagnostics and control devices

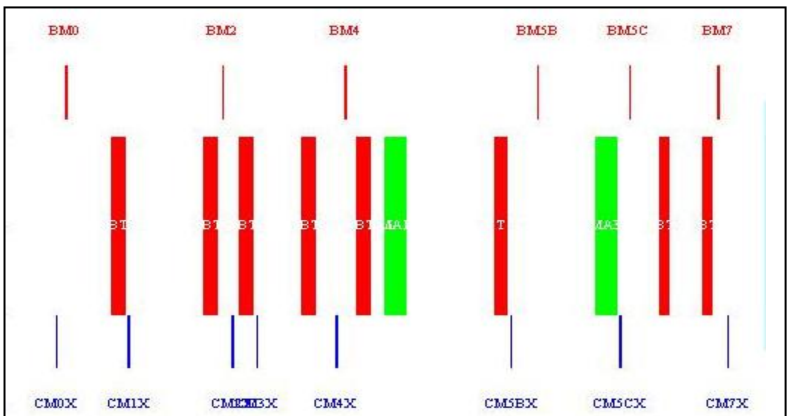


Figure 5.2. Configuration of BPM (red vertical line) and X/Y corrector (blue vertical line) in EMBT. Red and green blocks are quadrupoles and dipoles respectively.

- Figure 5.2 shows the BPM and corrector configuration in EMBT. Global performance of the entire system will be discussed in the following section.
- Orbit containment relies on the ambient field cancellation system discussed outside this note [11]. The residual level of ambient field after cancellation is 0.2 Gauss.
- Screens are placed in strategic locations for quick diagnosis of beam anomaly, efficient real time feedback on tuning and threading. Of particular usefulness is the screen near high dispersion point in the chicane for real time feedback on longitudinal phase space motivated tuning and diagnosis. This function is also performed

by the screen in EMBD with higher signal quality, although requiring more elaborate and disruptive procedures.

- Wires are capable of beam phase space diagnosis at higher intensity, although not capable of real time response as screens. They are placed at locations where potential need for high intensity diagnosis is identified.
- Configurations required for performing emittance measurement using a beam profile device (screen or wire) in conjunction with quadrupole scans have been established in the straight section of EMBT. The beam profile devices are at DB4 and DB6.
- A 100 W Faraday cup is placed at the EACA entrance for validating transmission. A 3 kW Faraday cup is at the end of EMBD for diagnosis at higher beam current.
- Momentum tail collimation will be done near the high dispersion point (EMBT:COL5A). Preliminary simulation [15] indicates that this can eliminate particles with $\Delta P/P$ greater than 2.5%, the main threat to off-bucket acceleration in the ACM and beyond. The remaining uncut "momentum tail" within this limit constitutes a few 10^{-4} of the beam. Complete longitudinal gymnastics in the linac and impact downstream will be examined in upcoming analysis.

5.2 EABT and EABD

<u>Overview</u>

EABT and EABD are mainly responsible for transporting beam from EACA exit to EHAT and providing fine adjustments as needed. For phase one these include

- Matching beam out of EACA into EACB-EHAT
- Performing transverse phase space diagnosis
- Performing RF setup for EACA and longitudinal phase space diagnosis.

Quadrupoles in EABT are used with those EHAT to shape overall optics and deliver matched beam into EHBT.

EABD consists of a 60° bend to branch the beam into subsequent spectrometer line with steering and focusing magnets, diagnostics and a 3kW Faraday cup in the dump. More detail of the diagnostics will be given in the section to follow.

Optics of EABT

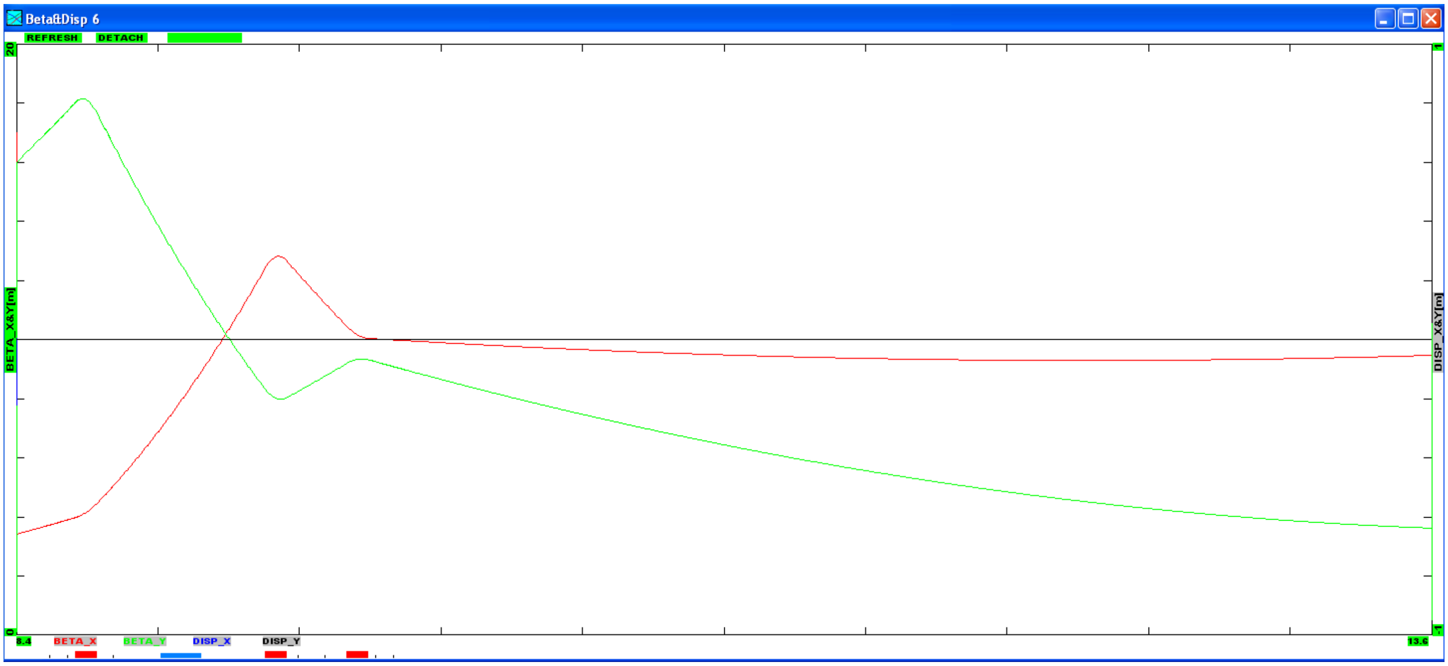


Figure 5.3 Optics of EABT and subsequent EACB (empty drift for phase one) showing β_X (red), β_Y (green). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-20 m for β_{XY}.

EABT will be geared for beam phase space and transport determination and matching adjustment all accomplished within its boundaries in future phases. In the current phase, in the absence of EACB and higher pass beam, some of these functions can be done in combination with EHAT. A consequence of this is that the optics shown in Figure 5.3 is not the only possibility for delivering matched beam to EHDT[7].

Configuration of BPM, corrector and other diagnostics

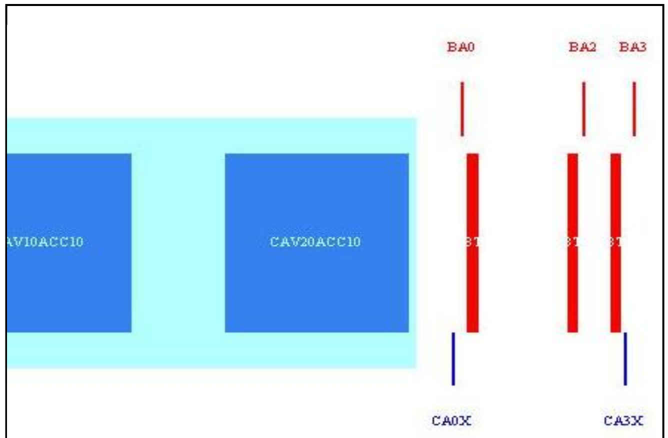


Figure 5.4. Configuration of BPM (red vertical line) and X/Y corrector (blue vertical line) in EABT. Red and cyan blocks are quadrupoles and ACM (EACA) respectively.

- Figure 5.4 shows the BPM and corrector configuration in EABT. Global performance of the entire system will be discussed in the following section.
- Orbit containment relies on the ambient field cancellation system discussed outside this note [11]. The residual level of ambient field after cancellation is 0.2 Gauss.
- Screens are placed in strategic locations for quick diagnosis of beam anomaly, efficient real time feedback on tuning and threading.
- Screen in EABD provides real time feedback on longitudinal phase space motivated tuning and diagnosis.
- Wires are placed at locations where potential need for high intensity diagnosis is identified.
- Configurations required for performing emittance measurement using a beam profile device (screen or wire)

[7] However in the interest of maintaining discipline for future phases of operation, we may consider "freezing" quad settings in EHAT as they will be in future phases.

in conjunction with quadrupole scans have been established. The beam profile devices are at DB2.

- A 100 W Faraday cup is placed at the EACB entrance for validating transmission. A 3 kW Faraday cup is at the end of EABD for diagnosis at higher beam current.

5.3 EHAT

Overview
EHAT in phase one is mainly responsible for transporting beam from EACB to EHBT and providing fine adjustments as needed. For these include

- Matching beam out of EACB into EHBT
- Performing transverse phase space diagnosis

Quadrupoles in EHAT are used with those EABT to shape overall optics and deliver matched beam into EHBT.

Optics of EHAT

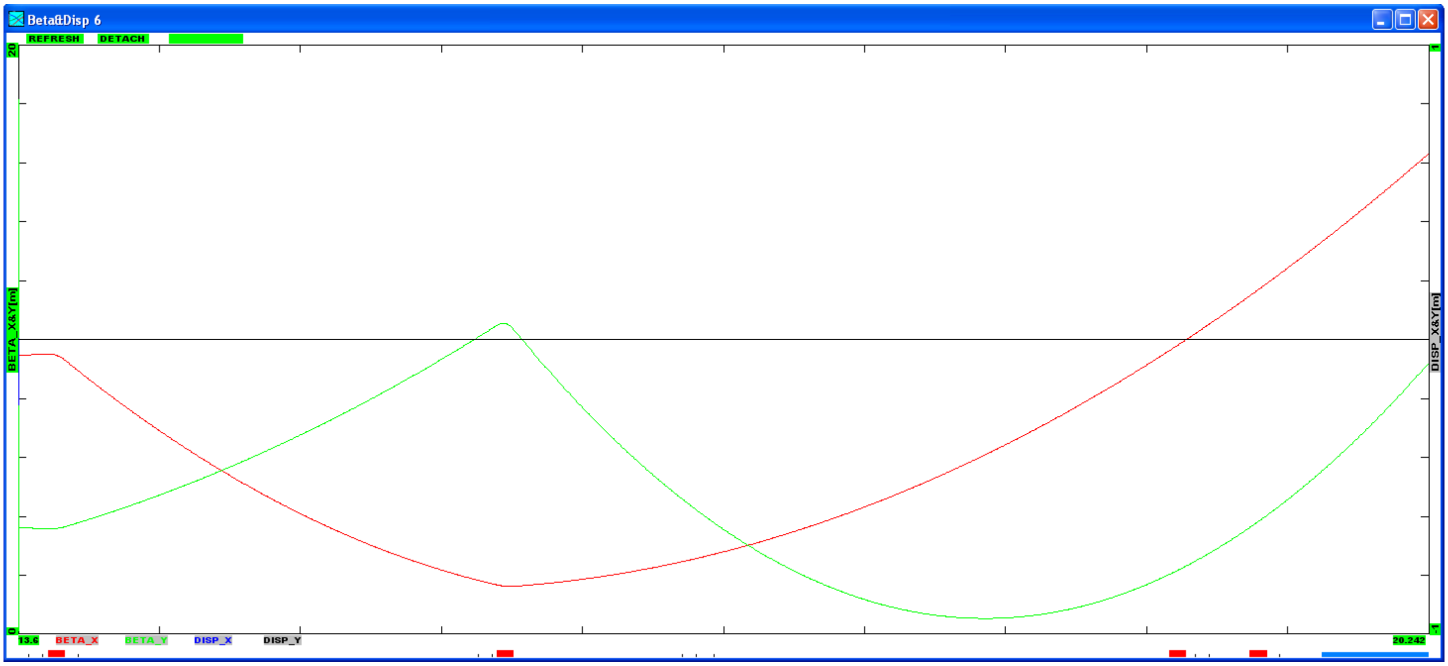


Figure 5.5 Optics of EHAT showing β_X (red), β_Y (green). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-20 m for β_{XY}. The last two quads and last dipole are not powered.

In phase 3 with two pass beams optics inside EHAT will be frozen and no quad in this section can be used as tuning quads. It will be an administrative decision during phase one commissioning whether to insist on this discipline.

In Figure 5.5 the last two quads and last dipole are not powered as functionally they belong to the tuning scheme of EHDT. The ability of delivering matched beam up to the 2nd-to-last quad has nonetheless been demonstrated.

Configuration of BPM, corrector and other diagnostics

- Figure 5.6 shows the BPM and corrector configuration in EHAT. Global performance of the entire system will be discussed in the following section.
- Orbit containment relies on the ambient field cancellation system discussed outside this note [11]. The residual level of ambient field after cancellation is 0.2 Gauss.

- Screens are placed in strategic locations for quick diagnosis of beam anomaly, efficient real time feedback on tuning and threading. One screen (EHAT:VS2) will be added in the next phase.
- Wires are placed at locations where potential need for high intensity diagnosis is identified.
- Configurations required for performing emittance measurement using a beam profile device (screen or wire) in conjunction with quadrupole scans have been established. The beam profile devices are at DB4.
- A 300 W Faraday cup is placed at the EACB exit.

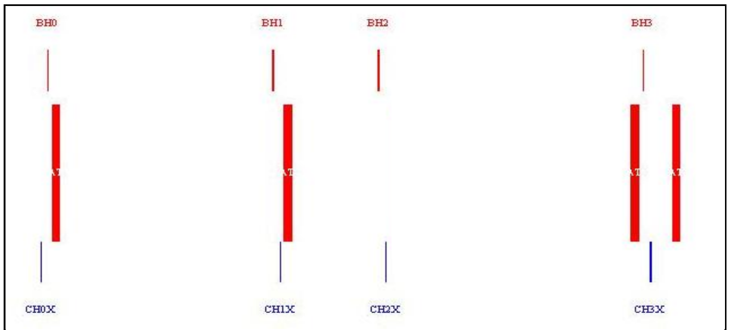


Figure 5.6. Configuration of BPM (red vertical line) and X/Y corrector (blue vertical line) in EHAT. Red blocks are quadrupoles.

5.4 Global Optics EMBT-EABT-EHAT

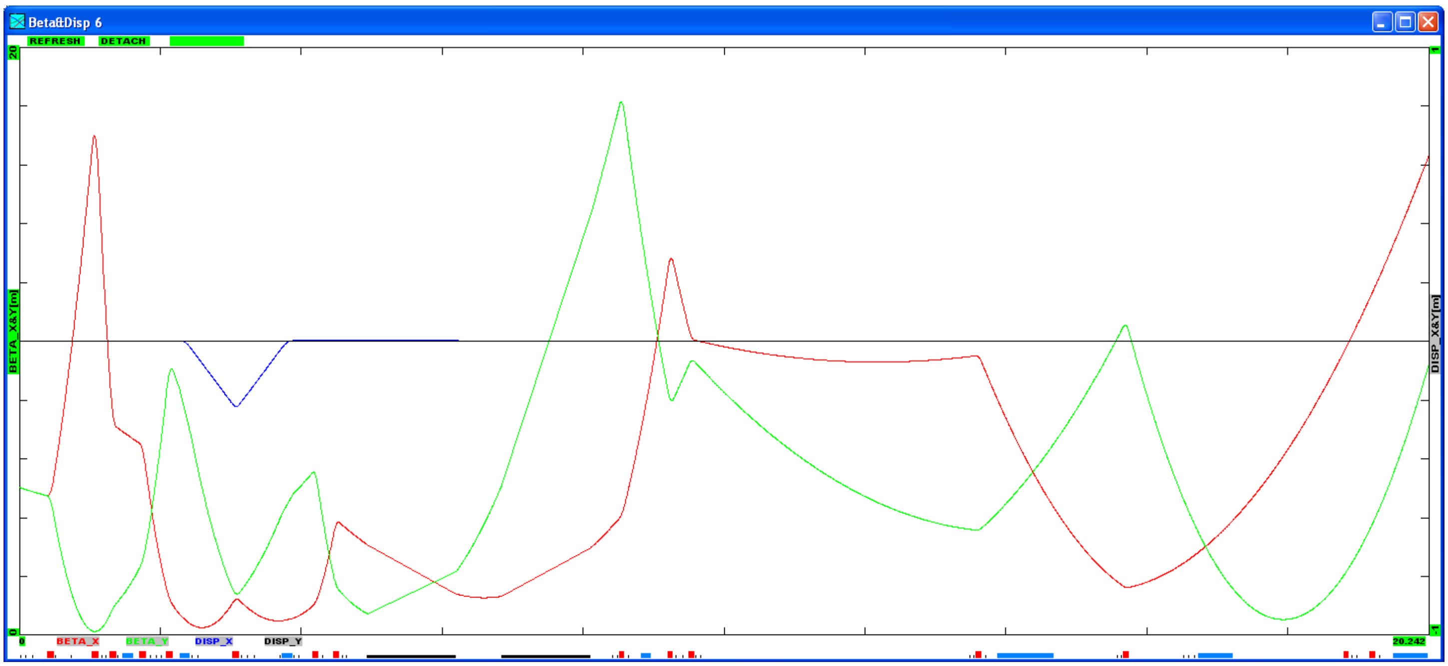


Figure 5.6 Optics of EMBT-EABT-EHAT showing β_X (red), β_Y (green), η_X (blue). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-20 m for β_{XY} and -1m to +1 m for η_X. The last two quads and last dipole are not powered.

5.5 EMBD Optics

The 10 MeV EMBD line will employ a dump designed to take 1 kW power. Optics tuning as far upstream as EMBT may be required to control the beam size at the center of the dump. This is acceptable as EMBT is a single pass operation. Baseline optical tuning is given in Figures 5.7 (a) and (b) corresponding to effective RMS beam size of 7 mm in both planes from combined betatron and dispersion contributions. This tuning requires EMBT:Q3 to be excited to maximum range (Section 7.1) while other quads being well below maximum.

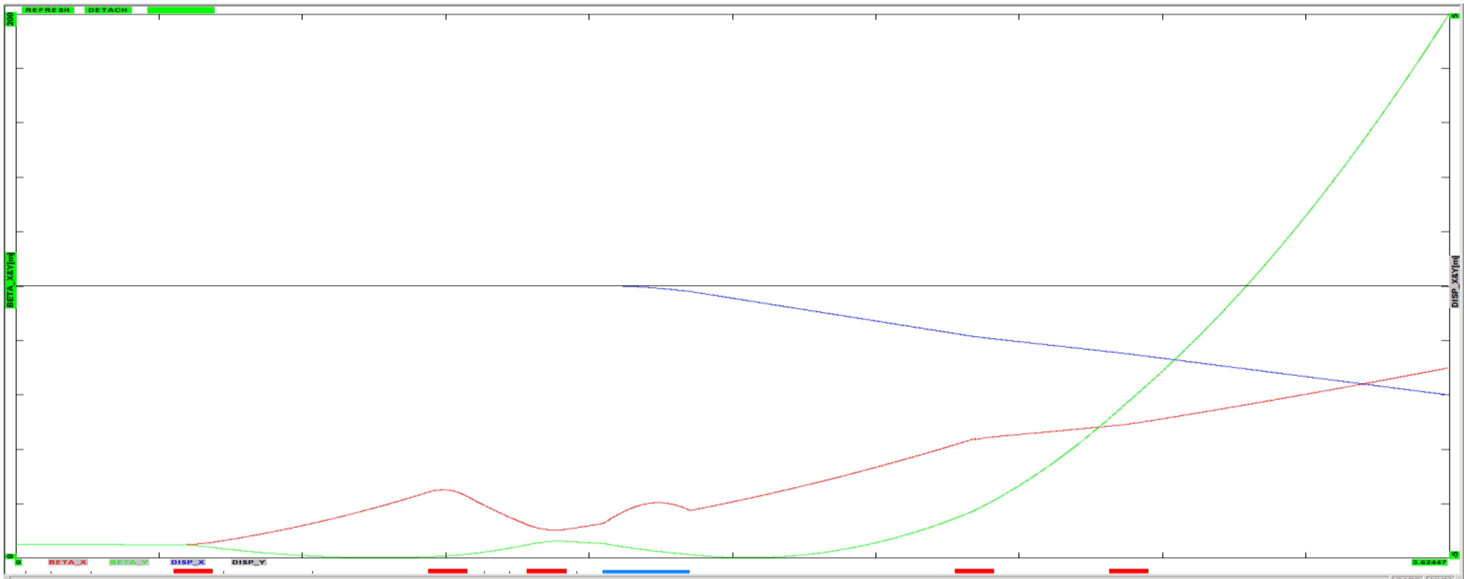


Figure 5.7(a) Optics of EMBT-EMBD showing β_X (red), β_Y (green), η_X (blue). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-200 m for β_{XY} and -5m to +5 m for η_X.

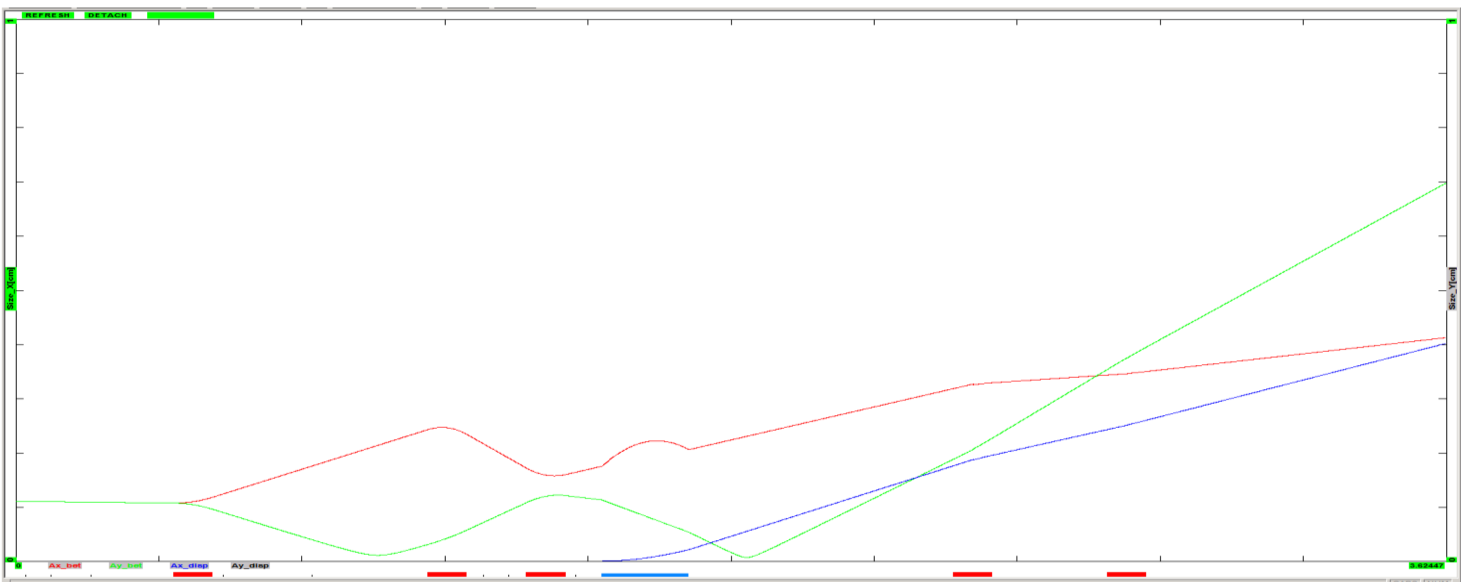


Figure 5.7(b) Beam size in EMBT-EMBD showing σ_X (red), σ_Y (green), $\sigma_P \times \eta_X$ (blue). Dipoles are indicated with blue boxes and quads with red boxes. Plot scales are 0-1 cm for all.

6 Residual Orbit Envelope and Overall Transverse Extent of Beam

Residual orbit envelope after correction

Several factors bear consequence to the requirement on maximum residual orbit and overall beam extent. With configuration of BPM's and correctors described in the previous section, and various alignment and hardware tolerances imposed as pre-requisites in section 3.6, the extent to which these requirements can be satisfied can be quantitatively demonstrated. We will discuss these criteria in the combined EMBT-EABT-EHAT system.

Figures 6.1 and 6.2 show that, with all errors within tolerances as spelled out in section 3.6, and the configuration as described in section 5.1 – 5.3, the 3σ corrected orbits in both planes fall within the design reqirement.

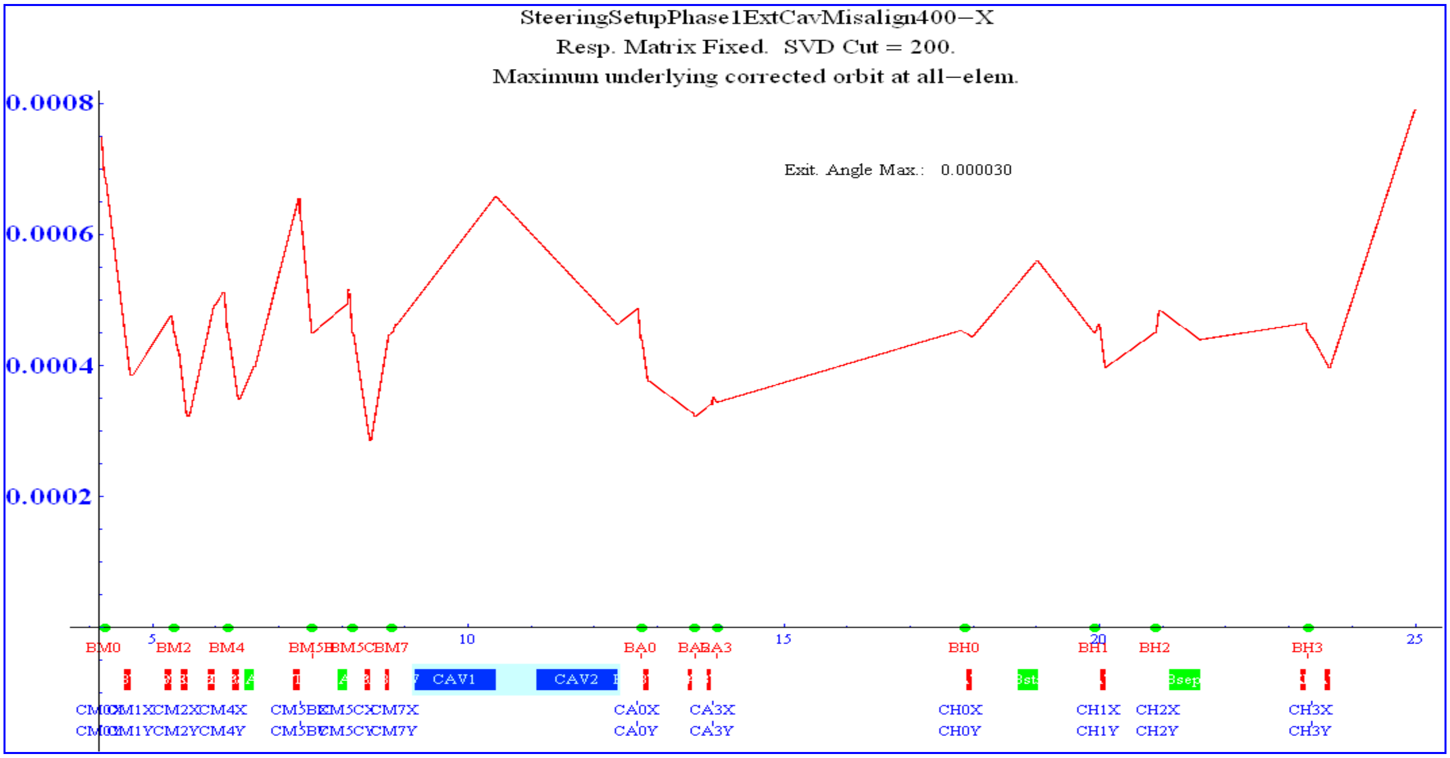


Figure 6.1. EMBT-EABT-EHAT 3σ corrected orbit (m) & end angle (rad) in X

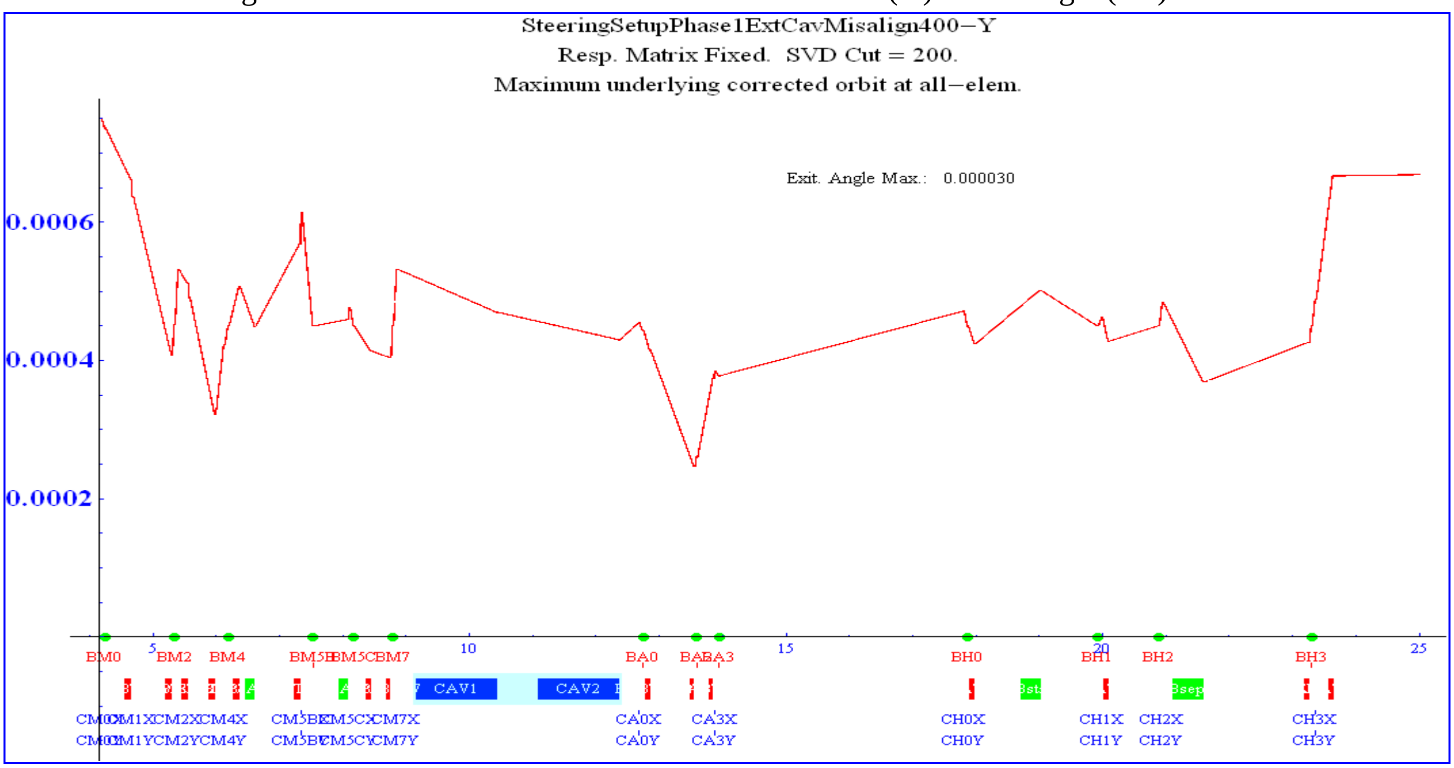


Figure 6.2. EMBT-EABT-EHAT 3σ corrected orbit (m) & end angle (rad) in Y

Combined beam and orbit extent

Combining beam size and residual orbit envelope, we arrive at pictures in Figures 6.3 and 6.4 showing 4.5σ of betatron beam, dispersive beam, and residual orbit distributions quadratically combined. This accounts for the entire combined transverse extent of the beam due to intrinsic emittance, optics, momentum spread, and all alignment, hardware and monitoring errors to the $<10^{-5}$ level.

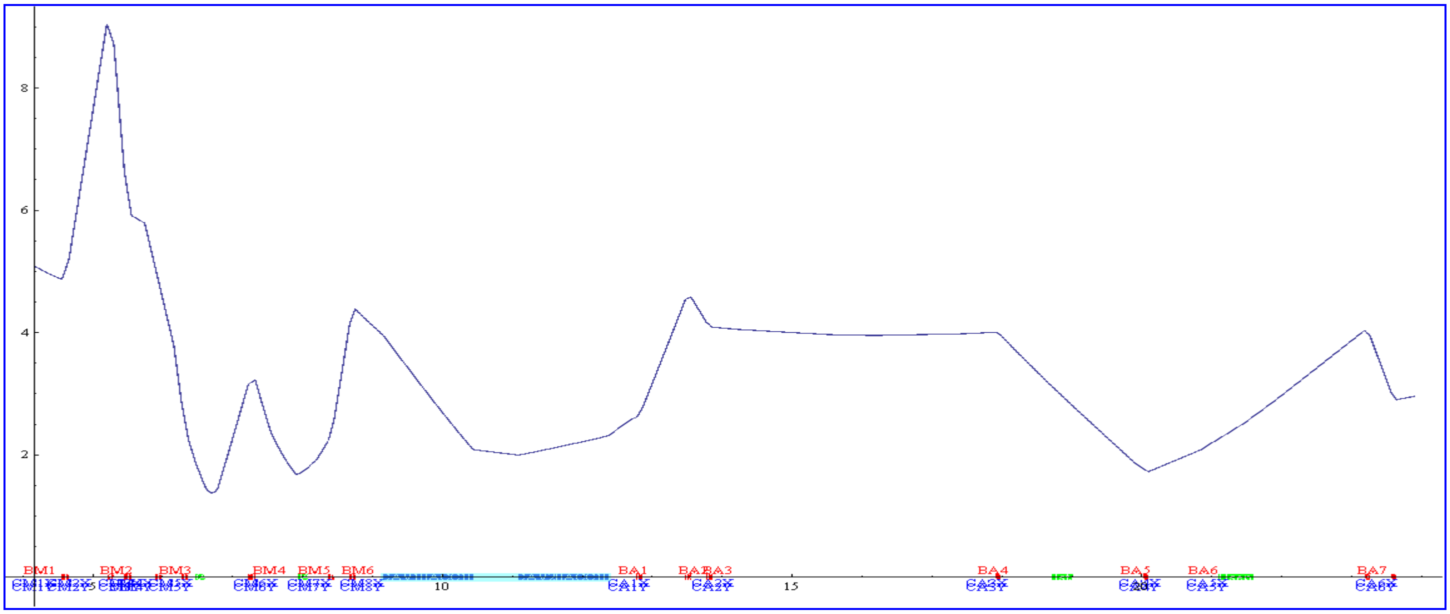


Figure 6.3. Combined 4.5σ envelope of betatron beam size, dispersive beam size, and residual orbit distribution in X (mm).

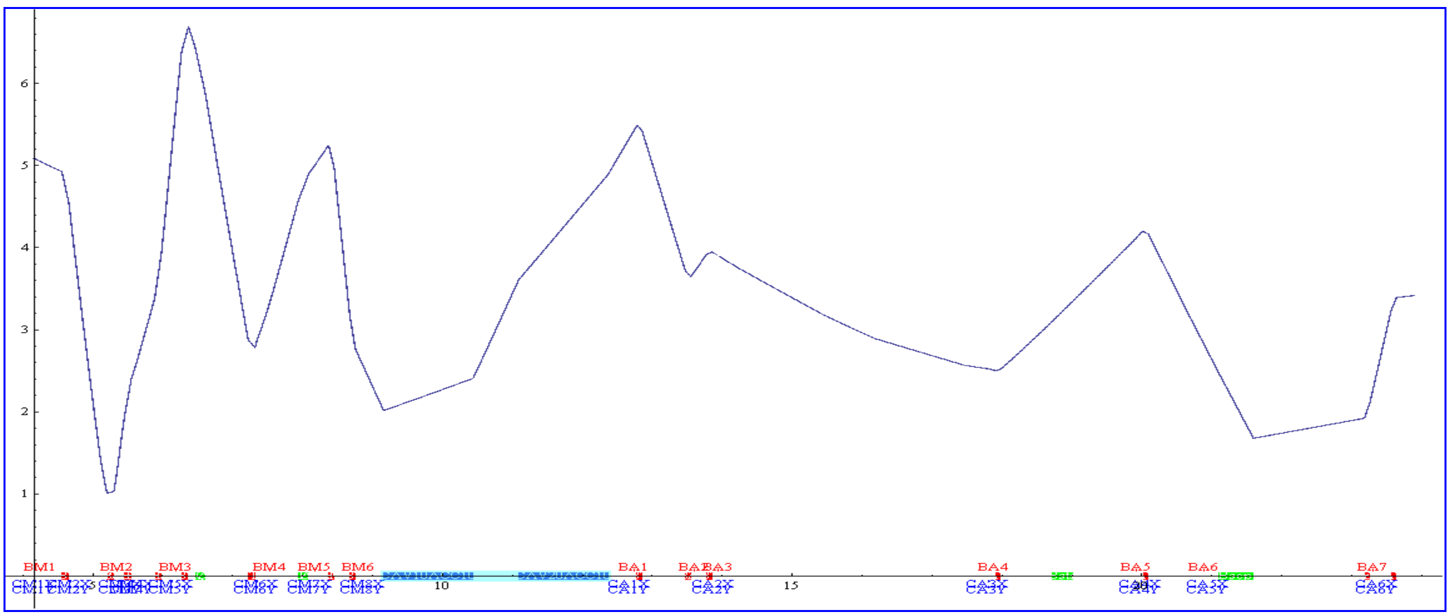


Figure 6.4. Combined 4.5σ envelope of betatron beam size, dispersive beam size, and residual orbit distribution in Y (mm).

Demand on correctors

It is important to also examine the corrector strength required to achieve the residual orbit envelopes in this context. Figures 6.5 and 6.6 show corrector strengths needed to combat combined error distribution at the 3σ extent. The larger demand on X-correctors is attributable to ambient field effects.

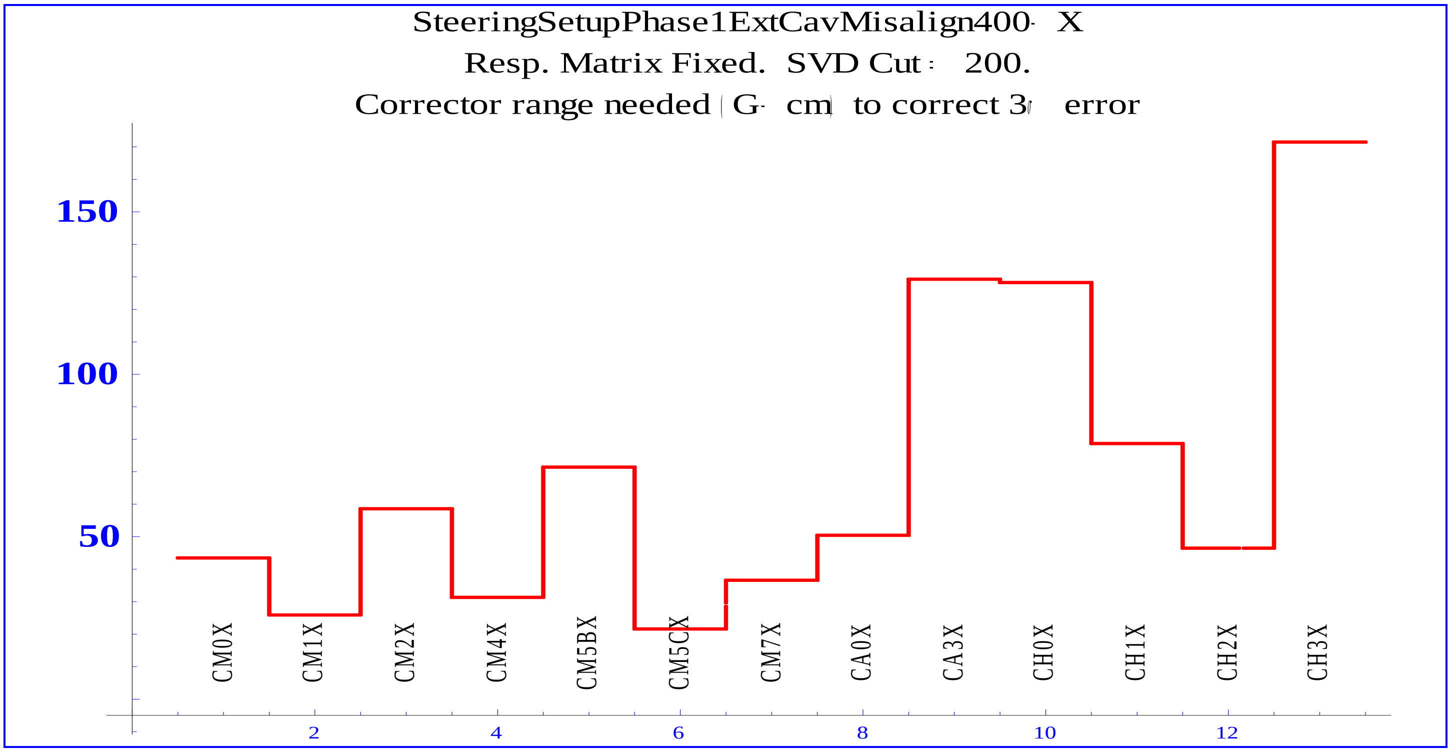


Figure 6.5. Corrector strength needed (G-cm) to combat 3σ error in X

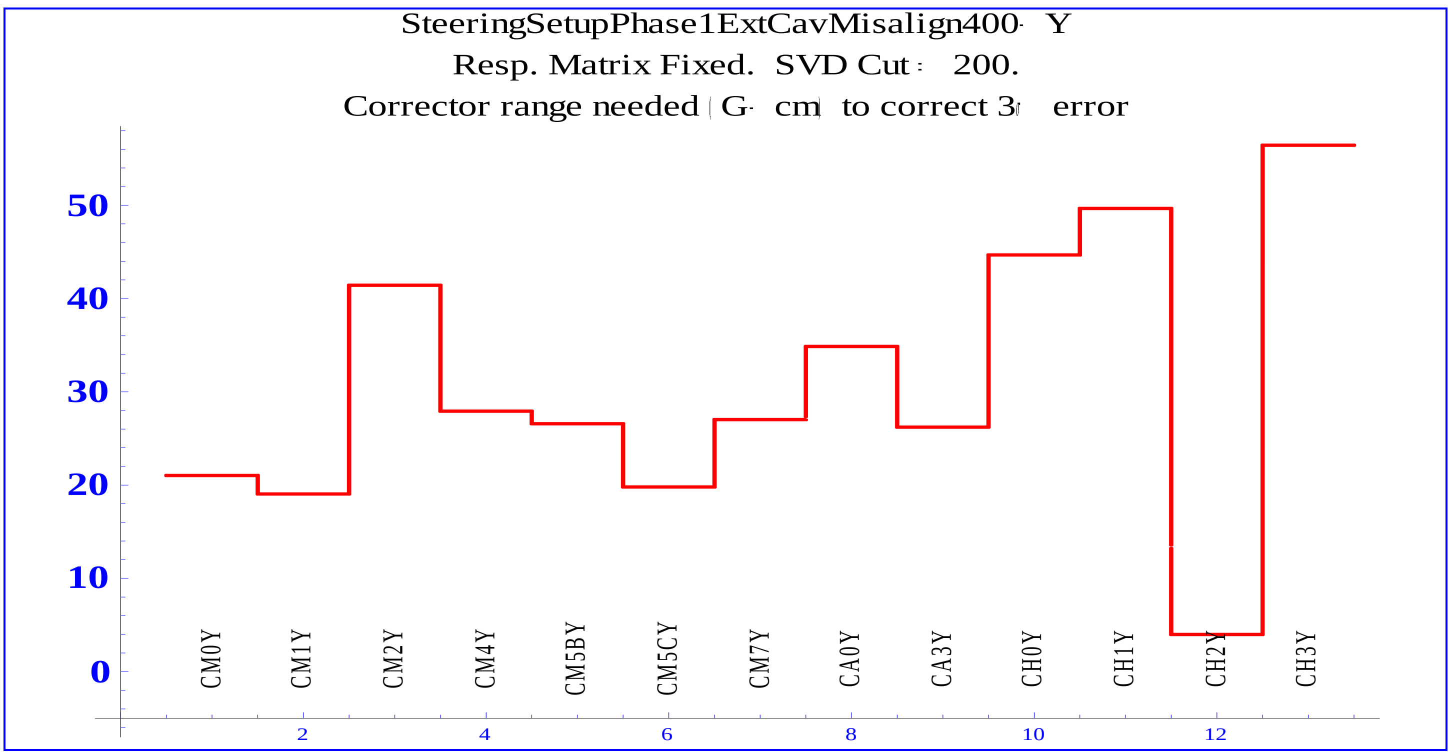


Figure 6.6. Corrector strength needed (G-cm) to combat 3σ error in Y

DC ambient field effects

We also examine the effect on the orbit caused by fixed ambient magnetic fields suppressed to the 0.2 Gauss level. As is different from preceding analysis based on stochastic error distribution, here the contributing factor is a constant deterministic force, and thus the effects are fixed offset in orbit and corrector setting.

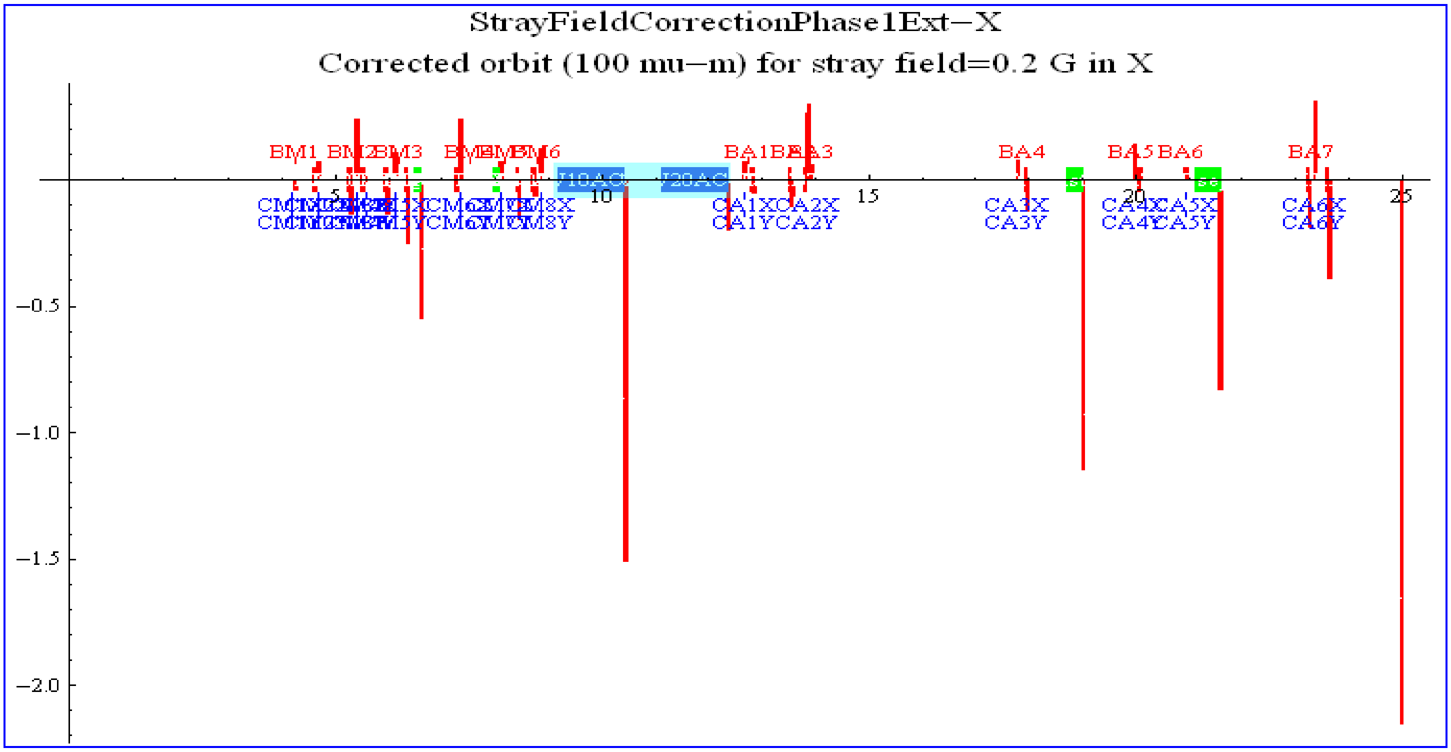


Figure 6.7. Corrected orbit in X (in 100 μm) due to 0.2 G uniform vertical ambient field

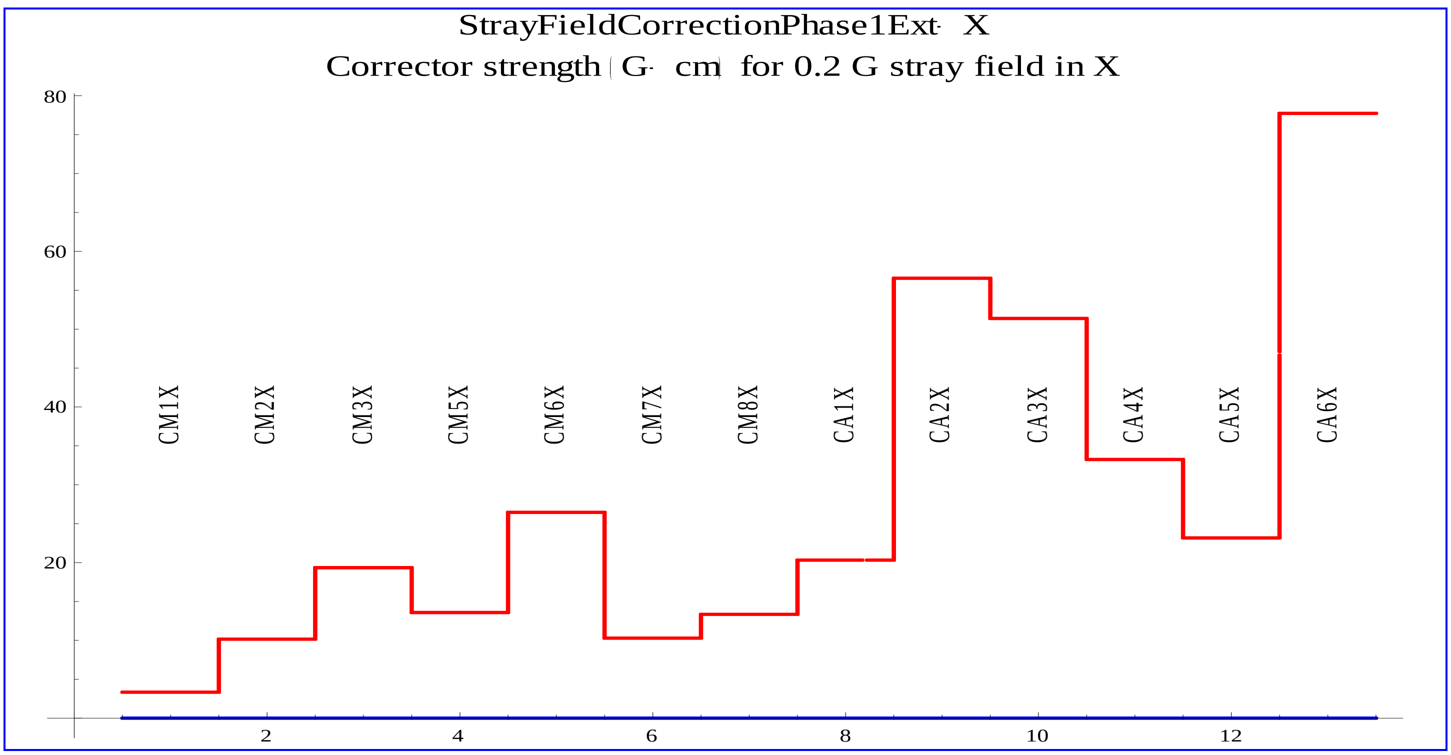


Figure 6.8. Corrector strength in X needed (G-cm) to combat 0.2 G uniform vertical ambient field

It is seen that the orbit after correction is mostly at <0.2 mm level. The demand on corrector is largely <40 G-cm except toward the end where large unshielded sections are present.

As mentioned in the introduction, this exercise has been applied to future phases of the E Linac, in particular the RLA and ERL modes with 2 beams in the EMBT-EABT-EHAT sections simultaneously. The demonstration of satisfaction of the above criteria in these future modes of operation, under the phase one physical layout, has been the pre-requisite for blessing the layout described in this note.

7 Component Lists – Dipoles and Quadrupoles

- All coordinates below are referred to cyclotron center (+X: East), +Y: North, +Z: Up). Z is at -609.60 mm for all elements described below.
- Coordinates for ACM cavities are not included as details of the final SRF designs are needed to translate optics design results into usable alignment specification for engineering.
- Despite this note being for Phase One only, magnetic field strength requirements have been defined in anticipation of eventual multi-pass operation.
- All magnets run on independent power supplies unless otherwise indicated.
- As noted in section 3.6, tolerance on stability of dipoles is 2×10^{-4} RMS.

7.1 EMBT and EMBD

Quadrupole*

	KdL (G)	Polarity**
EMBT:Q1	1250	B
EMBT:Q2	1250	B
EMBT:Q3	1250	B
EMBT:Q4	1250	B
EMBT:Q5	1250	B
EMBT:Q5B	1500	B
EMBT:Q6	1220	B
EMBT:Q7	1220	B
EMBD:Q1	1220	B
EMBD:Q2	1220	B

*Based on strengths at 15 MeV kinetic energy (1.5 times of nominal single pass energy), with NO margin added.
** B: Bipolar; U: Uni-polar

Dipole*

	Bend angle (°)	Path length (cm)	Entry angle (°)	Exit angle (°)	BdL (G-cm)
EMBD:MB0	60.0000	22.0	30.0	30.0	55000
EMBT:MB5A***	18.0000	15.25	9.00	9.00	16500
EMBT:MB5C***	18.0000	15.25	9.00	9.00	16500

* Strength at 15 MeV. No margin added
** EMBD dipole coordinates are for beam path at full bending strength to dump. Footprint of beam path on straight-ahead axis is 10.5 cm.
*** EMBT:MB5A and EMBT:MB5C will run in series off a single power supply.

7.2 EABT and EABD

Quadrupole*

	KdL (G)	Polarity**
EABT:Q1	1660	B
EABT:Q2	1660	B
EABT:Q3	1660	B
EABD:Q1	1660	B
EABD:Q2	1660	B

*Based on maximum strength among quad solutions for single pass at 45 MeV kinetic energy (1.5 times of nominal single pass energy), ERL at nominal energy and RLA at nominal energy[8] with NO margin added.
** B: Bipolar; U: Uni-polar

Dipole*

	Bend angle (°)	Path length (cm)	Entry angle (°)	Exit angle (°)	BdL (G-cm)
EABD:MB0	60.00	30.42	30.00	30.00	158964

* Strength at 45 MeV. No margin added
** EABD dipole coordinates are for beam path at full bending strength to dump. Footprint of beam path on straight-ahead axis is 15 cm.

7.3 EHAT

Quadrupole*

	KdL (G)	Polarity**
EHAT:Q1	2767$^{\pm}$	B
EHAT:Q2***	2767$^{\pm}$	B
EHAT:Q3****	4845	B
EHAT:Q4****	4773	B

*Based on maximum strength among quad solutions for single pass at 45 MeV kinetic energy (1.5 times of nominal single pass energy), ERL at nominal energy and RLA at nominal energy[9] with NO margin added.
** B: Bipolar; U: Uni-polar
***EHAT:Q2 may require larger bore in phase 3.
**** Per Y. Rao's DN on EHBT [3].
$^{\pm}$ Scaled to full E Linac energy 75 MeV

Dipole*

	Max. Bend angle (°)	Entry angle (°)	Max. BdL (G-cm)
EHAT:MB4**	34.00	0.00	147302

* Strength at 75 MeV. No margin added.

[8] Without considering possibility of single pass at 1.5 times nominal energy, these values are closer to the 1220 G in the EMBT table.
[9] Without considering possibility of single pass at 1.5 times nominal energy, these values are closer to the 1220 G in the EMBT table.

**EHAT:MB4 is a branching dipole which belongs in the EHBT/EHDT setup process [3]. Specs here are for maximum bending angle only. More detail is maintained in [16].

8 Installation Coordinate Tables

In all the following:

- S: Cumulative path length with S=0 at the cathode surface
- X: +:East; -: West in Cyclotron Center coordinate
- Y: +:North; -: South in Cyclotron Center coordinate
- Tweak: Allowed position tweaking from design baseline[10] along longitudinal (S) direction. The plus (minus) value gives the allowed range of movement downstream (upstream) along the beam line (NOT along X-Y axes). This column is only for the use by Design Office at the layout stage to arbitrate conflicts not foreseen in the optics design. It does not address alignment tolerance once the layout is final. Consult Appendix 1 for more specific prescriptions on allowed flexibility at the stage of element layout.
- All coordinates refer to element center, except for dipoles where coordinates are of entry-exit points.

The S-coordinates will be used for installation purpose as follows:

- Each contiguous section between Anchor points lies on a straight line.
- The X-Y coordinates of the beginning (ending) point of each section are those of the first (last) entry in the section.
- To obtain the path length from the beginning (ending) Anchor point to any element, subtract the S-coordinate of the element of interest by the S-coordinate of the beginning (ending) Anchor point.

8.1 EMBT-EABT-EHAT

	S (mm)	X (mm)	Y (mm)	Tweak (mm)	Note
EMBT:XCB0	4183.9	-35007.6	-7467.6	-50; +100	Anchor point
EMBT:YCB0	4183.9	-35007.6	-7467.6	-50; +100	
EMBT:BPM0	4248.9	-35045.8	-7415.	-50; +100	
EMBT:VS0	4348.9	-35104.6	-7334.1	±100	
EMBT:RFSH0	4348.9	-35104.6	-7334.1	±100	
EMBT:Q1	4608.9	-35257.4	-7123.7	±10	
EMBT:XCB1	4683.9	-35301.5	-7063.1	±100	
EMBT:YCB1	4683.9	-35301.5	-7063.1	±100	
EMBT:Q2	5058.9	-35522.	-6759.7	±10	
EMBT:BPM2	5148.9	-35574.9	-6686.9	±100	
EMBT:XCB2	5213.9	-35613.1	-6634.3	±100	
EMBT:YCB2	5213.9	-35613.1	-6634.3	±100	
EMBT:Q3	5502.9	-35782.9	-6400.5	±10	
EMBT:XCB3	5577.9	-35827.	-6339.8	±100	
EMBT:YCB3	5577.9	-35827.	-6339.8	±100	
EMBD:MB0 Entry	5644.4	-35866.1	-6286.	0	Exit is in EMBD
EMBD:MB0 Exit	5794.4	-35954.3	-6164.6	0	Place holder
EMBT:Q4	5935.9	-36037.4	-6050.2	±10	
EMBT:VS4	6045.9	-36102.1	-5961.2	±100	

[10] Without interference with immutable elements.

EMBT:FWS4	6045.9	-36102.1	-5961.2	±100	
EMBT:RFSH4	6045.9	-36102.1	-5961.2	±100	
EMBT:XCB4	6130.9	-36152.1	-5892.4	±100	
EMBT:YCB4	6130.9	-36152.1	-5892.4	±100	
EMBT:BPM4	6195.9	-36190.3	-5839.8	±100	
EMBT:Q5	6318.9	-36262.6	-5740.3	±10	
EMBT:MB5A Entry	6463.3	-36347.4	-5623.5	0	Anchor point
New Segment Starts					
EMBT:MB5A Exit	6615.8	-36416.4	-5488.2	0	Anchor point
EMBT:XCB5A	6640.8	-36424.1	-5464.4	±100	Stand alone corr.
EMBT:YCB5A	6640.8	-36424.1	-5464.4	±100	Stand alone corr.
EMBT:COL5A	7074.1	-36558.	-5052.3	+100; -50	
EMBT:Q5B	7274.1	-36619.8	-4862.1	±10	
EMBT:XCB5B	7349.1	-36643.	-4790.8	±100	
EMBT:YCB5B	7349.1	-36643.	-4790.8	±100	
EMBT:FWS5B	7434.1	-36669.3	-4709.9	+50; -100	
EMBT:RFSH5B	7434.1	-36669.3	-4709.9	+50; -100	
EMBT:VS5B	7434.1	-36669.3	-4709.9	+50; -100	
EMBT:BPM5B	7534.1	-36700.2	-4614.8	±100	
EMBT:YCB5B2	7907.4	-36815.5	-4259.8	±100	
EMBT:MB5C Entry	7932.4	-36823.2	-4236.	0	Anchor point
New Segment Starts					
EMBT:MB5C Exit	8084.9	-36847.	-4086.	0	Anchor point
EMBT:XCB5C	8109.9	-36847.	-4061.	±100	
EMBT:YCB5C	8109.9	-36847.	-4061.	±100	
EMBT:BPM5C	8174.9	-36847.	-3996.	±100	
EMBT:Q6	8412.9	-36847.	-3758.	±10	
EMBT:VS6	8512.9	-36847.	-3658.	±100	
EMBT:RFSH6	8512.9	-36847.	-3658.	±100	
EMBT:FC6	8512.9	-36847.	-3658.	±200	
EMBT:Q7	8713.8	-36847.	-3457.1	±10	
EMBT:BPM7	8893.8	-36847.	-3277.1	-100; +50	
EMBT:XCB7	8958.8	-36847.	-3212.1	-100; +50	
EMBT:YCB7	8958.8	-36847.	-3212.1	-100; +50	
EACA Center	10764.5	-36847.	-1406.4	0	Reference point
EABT:XCB0	12580.3	-36847.	409.4	-50; +100	
EABT:YCB0	12580.3	-36847.	409.4	-50; +100	
EABT:BPM0	12645.3	-36847.	474.4	-50; +100	
EABT:Q1	12815.3	-36847.	644.4	±10	
EABT:VS1	12915.3	-36847.	744.4	±100	
EABT:RFSH1	12915.3	-36847.	744.4	±100	
EABD:MB0 Entry	13089.6	-36847.	918.6	0	Exit is in EABD
EABD:MB0 Exit	13239.6	-36847.	1068.6	0	Place holder
EABT:Q2	13513.8	-36847.	1342.9	±10	
EABT:BPM2	13593.8	-36847.	1422.9	±100	
EABT:VS2	13693.8	-36847.	1522.9	±100	

EABT:RFSH2	13693.8	-36847.	1522.9	±100	
EABT:FC2	13693.8	-36847.	1522.9	±200	
EABT:Q3	13813.8	-36847.	1642.9	±10	
EABT:XCB3	13878.8	-36847.	1707.9	-100; +0[&]	
EABT:YCB3	13878.8	-36847.	1707.9	-100; +0[&]	
EABT:BPM3	13943.8	-36847.	1772.9	-100; +0[&]	
EHAT:XCB0	17806.	-36847.	5635.1	-0; +100[&]	
EHAT:YCB0	17806.	-36847.	5635.1	-0; +100[&]	
EHAT:BPM0	17871.	-36847.	5700.1	-0; +100[&]	
EHAT:Q1	17941.	-36847.	5770.1	±10	
EHAT:VS1	18041.	-36847.	5870.1	±100	
EHAT:RFSH1	18041.	-36847.	5870.1	±100	
EHAT:FC1	18041.	-36847.	5870.1	±200	Port only phase 1
EHAT:YCB1A	18150.			±50	Not in phase 1**
RF Sep entry	18215.	-36847.	6044.1	0	Not in phase 1**
RF Sep exit	18715.	-36847.	6544.1	0	Not in phase 1**
Bsteer entry	18715.	-36847.	6544.1	0	Not in phase 1**
Bsteer exit	19015.	-36847.	6844.1	0	Not in phase 1**
EHAT:BPM1	19925.	-36847.	7754.1	+100; -50	
EHAT:XCB1	19990.	-36847.	7819.1	±100	
EHAT:YCB1	19990.	-36847.	7819.1	±100	
EHAT:Q2	20055.	-36847.	7884.1	±10	
EHAT:BPM2	20885.	-36847.	8714.1	+100; -50	
EHAT:XCB2	20950.	-36847.	8779.1	±100	
EHAT:YCB2	20950.	-36847.	8779.1	±100	
EHAT:VS2	21035.	-36847.	8864.1	+100; -50	Not in phase 1**
EHAT:RFSH2	21035.	-36847.	8864.1	+100; -50	
EHAT:FWS2	21035.	-36847.	8864.1	+100; -50	
Bseptum entry	21095.	-36847.	8924.1	0	Not in phase 1**
Bseptum exit	21595.	-36847.	9424.1	0	Not in phase 1**
EHAT:ACCT2	22920.9	-36847.	10750.	±100	
EHAT:Q3	23220.9	-36847.	11050.	±10	
EHAT:XCB3	23365.9	-36847.	11195.	±100	
EHAT:YCB3	23365.9	-36847.	11195.	±100	
EHAT:BPM3	23480.9	-36847.	11310.	±100	
EHAT:Q4	23600.9	-36847.	11430.	±10	
EHAT:VS4	23700.9	-36847.	11530.	+200; -50	
EHAT:FC4	23700.9	-36847.	11530.	+200; -50	
EHAT:MB4 Entry	23900.9	-36847.	11730.	0	Anchor point Exit is in EHDT

** All elements not included in phase one but needed for future phases are listed due to potential space allocation and diagnostics box design concerns.
*** Exit points of spectrometer dipoles EMBD:MB0 and EABD:MB0 are listed due to potential space allocation concerns. The true exit coordinates lie inside spectrometer lines.
**** Coordinates of ICM (EINJ) & ACM (EACA) walls are being confirmed. Tweaking allowances for correctors and BPM's next to EINJ and EACA have been set to reflect their immutability.

***** Dipole entry/exit points correspond to such points in optics modeling taking into account effective field extent. Their significance in the current context is more to serve as legitimate delimiting anchors to define intervening elements than to indicate on how the dipole itself will be installed, which will require further detail from the dipole design.

[&] Tweak ranges for these elements assume an immutable cryomodule footprint. Finalized cryomodule dimensions may result in relaxed tweak range for these elements beyond given.

8.2 EMBD*

	S (mm)	X (mm)	Y (mm)	Tweak (mm)	Note
EMBD:MB0 Entry	5644.4300	-35866.110	-6286.0000	0	Inside EMBT
EMBD:MB0 Exit	5864.3400	-35888.060	-6077.1500	0	Anchor point
EMBD:YCB0	6059.6400	-35808.580	-5898.7300	±10	
EMBD:Q1	6584.3400	-35595.210	-5419.3950	±20	
EMBD:XCB1	6674.400	-35558.580	-5337.1200	±10	
EMBD:YCB1	6674.400	-35558.580	-5337.1200	±10	
EMBD:BPM1	6824.3400	-35497.590	-5200.1400	±100	
EMBD:Q2	6974.3400	-35436.585	-5063.1100	±20	
EMBD:XCB2	7062.0400	-35400.930	-4982.9900	±10	
EMBD:YCB2	7062.0400	-35400.930	-4982.9900	±10	
EMBD:VS2	7294.3400	-35306.430	-4770.7800	±100	
EMBD:FWS2	7294.3400	-35306.430	-4770.7800	±100	Anchor point
EMBD:FC2 EPICS Name	7590.8600	-35185.850	-4499.8700		

8.3 EABD*

	S (mm)	X (mm)	Y (mm)	Tweak (mm)	Note
EABD:MB0 Entry	13089.6	-36847.000	918.63000	0	Inside EABT
EABD:MB0 Exit	13403.7	-36997.000	1178.4400	0	Anchor point
EABD:YCB0	13613.7	-37178.860	1283.4400	±100	
EABD:Q1	14233.7	-37715.800	1593.4400	±20	
EABD:XCB1	14283.7	-37759.100	1618.4400	±100	
EABD:YCB1	14283.7	-37759.100	1618.4400	±100	
EABD:BPM1	14473.7	-37923.640	1713.4400	±100	
EABD:Q2	14623.7	-38053.550	1788.4400	±20	
EABD:XCB2	14648.7	-38075.200	1800.9400	±100	
EABD:YCB2	14648.7	-38075.200	1800.9400	±100	
EABD:VS2	14943.7	-38330.670	1948.4400	±100	
EABD:FWS2	14943.7	-38330.670	1948.4400	±100	
EABD:FC2	15063.7	-38434.600	2008.4400	±200	Anchor point

* Revised dimensions to clear interference in both lines require optical tuning using quads further up the main beam line before the dipoles. This does not result in exceeding quad strength specs and is acceptable since no multiple pass operation is involved.

9 References

1. Official ELBT design note is at https://documents.triumf.ca/docushare/dsweb/Get/Document-34348/TRI-DN-10-08.pdf.
2. For most recent ELBT solution which defines the input to EMBT see http://elinac.triumf.ca/e-linac/wbs-areas/injector/electron-gun/presentations/FinalBaselineSolutions_New9Cell.pdf/view
3. Y-N. Rao, EHBT Design Note. http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/phase-1-review-2012-april-05/ehbt/on_EHBT_optics.pdf/view
4. S. Koscielniak, E-linac requirements list, Feb. 14, 2011.
5. R. Baartman, Qauds for ARIEL electrons, TRIUMF Beam Physics Note, TRI-BN-11-02, July, 2011.
6. Input from T. Planche.
7. Input from T. Emmens & T. Ries
8. Recommendation from Beam Physics Meeting.
9. EMBT dipole tolerance on sextupole component http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/magnets/EMBT%20dipole%20sextupole%20tolerance%20NEW.pdf/view
10. R. Baartman, EMBT dipole tolerance on sextupole component. http://lin12.triumf.ca/text/design_notes/b2012_01/Sext_in_Dipole.pdf
11. R. Baartman, Magnetic field compensation for E-Linac. http://lin12.triumf.ca/text/design_notes/b2010_03/TRI-BN-10-03.pdf

    R. Baartman, Shielding the ARIEL beam pipe, http://lin12.triumf.ca/text/design_notes/b2011_03/Shielding.pdf
12. For detailed description of optical solutions and analysis of error tolerance, control configuration and other operation related issues for baseline single pass and 2-pass ERL and RLA, see http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/embt-eabt-ehat/EMBT_EABT_EHAT_Config_AnalysisD.pdf/view. However the single pass mode in this note has the 3-bend merger for EMBT.
13. ⇒ Needs updating. Complete coordinate information for all elements in sections described in this note, plus EGUN, ELBT and ELBD can be found at http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/phase-1-review-2012-april-05/Coordinate%20table%20All%20elements.pdf/view.
14. Some optics plots, including exception case solutions, especially concerning phase one, are in http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/embt-eabt-ehat/Phase1_Optics.pdf/view.
15. Input from F. Jones.
16. E Linac Optical Element Spreadsheet http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/phase-1-review-2012-april-05/ehbt/Book1_v71.xls/view
17. For diagnostics configuration presented at April 2001 external review, see http://elinac.triumf.ca/e-linac/wbs-areas/beamlines/diagnostics/meetings/triumf/2011-april-19-external-review/Review_April2011.pdf/view.

10 Appendix 1. Tolerance in Coordinates and Rules for Position Tweaking

Tweaking allowances to coordinates in this and related documents were given in Sections 3.2 and 3.3. The dipoles, quadrupoles, solenoids, RF buncher and (future) ICM/ACM coordinates are immutable. Position tweaking of other elements can be necessary due to interference and space constraints. The following may provide a working set of guidelines regarding how much freedom one has in tweaking BPM and steerer positions without violating the design principle during final beam line layout.

Hierarchical rules regarding BPM/steerer position tweaking (This does not apply to other devices):

0. Explicitly prohibited element moves to be specified in the coordinate tables supersede all rules below.

A. BPM's should be as far from each other as possible. Unless specified otherwise in coordinate table, they should be at least 1 m apart from each other.

B. It does not matter if a BPM immediately before (after) a quad or dipole (no more than 50 cm long) is relocated immediately after (before) the same quad/dipole. The word "immediately", meaning flange to flange, is important and has to apply in both qualifiers.

C. Movements within position tolerance given in the tables (tweaking allowance) are allowed.

Steerers follow the same rules as BPM's within its own group. There is no rule governing the relative positioning between BPM's and steerers other than specified in the coordinate table, except

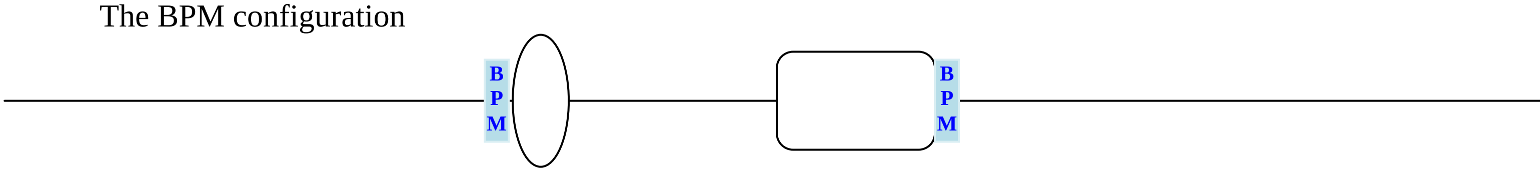
D. While conforming to all above rules, steerers should precede BPM's in its vicinity as much as possible, especially if they are on opposite ends of another element.

Example 1:

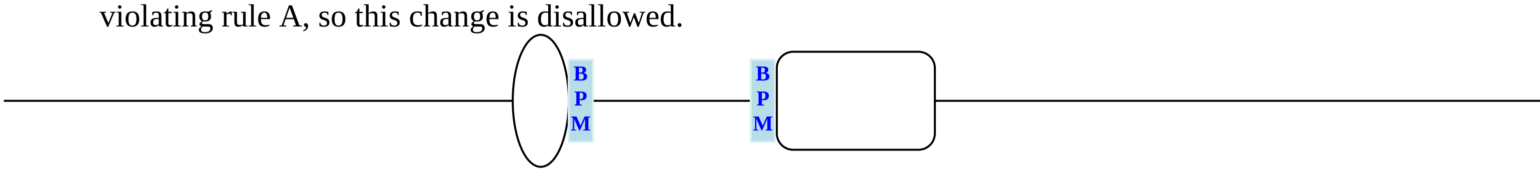
A BPM is immediately after a 50 cm dipole. The position tolerance given is ±5 mm. So by rule C it can move downstream by 5 mm, and by rule B it can move upstream by 50 cm to immediately before the dipole assuming no higher rules are violated.

Example 2:

The BPM configuration

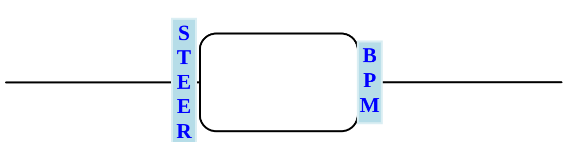


can be changed to the one below by rule B, but this will cause them to be within 1 m of each other, violating rule A, so this change is disallowed.



Example 3:

Unless there are insumountable difficulties, or higher rules are violated otherwise, try not to turn this configuration



into this (by rule D):

In addition to the above, the ordering between solenoids and steerers should be strictly followed as in the table.