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History of Changes

Release Number	Date	Description of Changes	Author(s)
1	June 25, 2012	Revised in response to 2012 May 1–3's Review comments	Y. –N. Rao
2	Oct. 17, 2012	Revised in response to 2012 Sept.–Oct.'s Beam Modes Task Force discussion results	Y. –N. Rao
3	Feb. 19, 2013	Revised the table on page 32 for quad EHBTW:Q4, in response to E. Guetre's request	Y. –N. Rao
4	Apr. 12, 2013	Revised the tables in Sections 13 and 14 by (1) adding up one decimal place to each element's coordinates; (2) adding up the cross-over point coordinates of dipoles; (3) fine adjusting and/or correcting magnets and diagnostic elements coordinates. In addition, added statements for the quads requiring polarity reversal for demagnetizsation.	Y. –N. Rao
5	Jun. 14, 2013	In response to the higher level's request, made following changes: (1) moved BPM6 downstream to BPM7; (2) removed KICKER39 and replaced SEPTUM41 with dipole magnet MB41.	Y.-N. Rao
6	Jul. 16, 2014	In response to E.Guetre's and S. Koscielniak's dictations, made following changes in the table under Section 14: (1) moved FC8 and BPM8 downstream by 8.5cm for adding shielding; (2) moved VS11 upstream by 22.839cm, to avoid interferences; (3) moved FWS35 downstream by 2cm to avoid interference with Q35.	Y.-N. Rao

1 Abstract

The Electron High Energy Beam Transport (EHBT) is defined in this document in terms of the optics design, geometrical layout and element coordinates, and element specifications.

2 Objective

The EHBT shall deliver electrons from the electron accelerator transport (EHAT) to 500 kW East, and 100 kW West, convertor and target modules. This note describes the design of EHBT magnetic optics, covering major element coordinates and performance specifications in sufficient details for proceeding with engineering design.

3 Definitions

- **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.
- **Beam profile monitor:** The beam profile monitor herein is meant either a view screen (VS) or a fast wire scanner (FWS), measuring both x and y profiles. Because the wire scanner is better at discerning tails and halos than the view screen, we shall put wire scanners at locations where the momentum dispersion reaches maximum to monitor the halos. In other locations, we shall use screens for routine check of beam behavior and rough characterization, as they are faster in getting profile information.
- **Knob:** By knob is meant settable optical parameter. Implementation may be either through one-to-one correspondence between set point and a single independent power supply, or multiple supplies under software control as a single set point.
- **In-dipole corrector:** By in-dipole corrector herein is meant additional windings attached to a regular dipole and excited with an independent precision power supply, or a regular dipole excited with an additional precision trim power supply, to serve as a beam corrector. Such corrector shall be used where the space does not allow the regular XY-corrector magnet. It shall have the same strength (up to 500 Gauss-cm) as the regular ones.
- **Intrinsic beam size:** is defined as $\sqrt{\beta\epsilon}$, where β is the betatron amplitude function and ϵ is the beam emittance. On average $\beta = 3.0$ m. The nominal emittance is ϵ=6 μm (r.m.s., normalized). The calculations described in this note were performed for 6 μm.
- **Optical and diagnostic element indexing:** are defined in Section 13 and Section 14 separately.

4 Requirements and Constraints

4.1 Top Level Requirements [1]

- EHBT shall be capable to transport electrons with energy between 20 and 75 MeV.
- Shall be capable to provide electrons to either target at one time and to both targets simultaneously with switching rate larger than 500 Hz.
- Shall be consistent with later implementation of proton beam line (BL4N) on the West station.

4.2 General Requirements

- simple and robust.
- low loss.
- easy to tune.
- easy to maintain.
- within CFI budget and schedule.

4.3 Specific Requirements

- Shall be capable to transport electrons with loss less than 10^{-5}/meter [2].
- Shall provide 10 mm×10 mm full width square/round spot on West convertor/target [3].
- Shall provide 20 mm×20 mm full width square/round spot on East convertor/target [3].
- Target group must provide information such as the peak and average density permitted, beam distribution and halo permitted, etc.
- Shall keep beam centroid displacement from the axis below 1.0 mm at strong quadrupoles so the quadrupole intrinsic-aberration-caused emittance growth is less than 0.5%.

4.4 General Constraints

- The layout shall fit within the ARIEL and e-hall building civil construction footprint.
- The layout shall be consistent with the envelope of proton beam line.

- EHBT shall enter both targets at the same elevation as proton beam line.
- Shall stay within CFI budget and schedule: where possible, the number of magnet types shall be minimized.

4.5 Specific Constraints

- EHBT shall be at $266.5'$ level in the e-hall [4].
- EHBT shall be at $265.5'$ level in the tunnel [4].
- EHBT shall be at $268.5'$ level entering either target [4].
- The last magnetic element of EHBT shall stay $\geq 5.2\,\text{m}$ from the target, upstream from the shielding wall.
- EHBT shall match the EHAT optical parameters at location ($x = -36.8470\,\text{m}$, $y = +10.9300\,\text{m}$, $z = -0.6096\,\text{m}$) as defined in the global Cartesian system.
- The incoming beam condition shall be: ϵ=6 μm (r.m.s., normalized), $\delta p/p = 0.75 \times 10^{-3}$ (r.m.s.) at 75 MeV while the extreme value [5] of $\delta p/p$ is -3.3×10^{-3} at 75 MeV.

4.6 Working Assumptions

- At either target, the instantaneous electron beam size shall be $\geq$1 mm (FWHM), and flexible up to 3 mm. This can be achieved by simply tuning the last 2 doublets.
- The allowed insertion length shall be 17.5 cm for the long quadrupoles (which have integrated strength over 0.5 Tesla), and 15.0 cm for the short ones [10].
- The allowed insertion length (rectangular shape) shall be 32.23 and 15.60 cm [14] respectively for the large and small dipoles.
- The dipoles EHBT:MB25,29,33,37 and EHBTE:MB6 shall be of exactly the same design [6], that is, rectangular shape, maximum B-field strength $\geq$0.67 Tesla, and maximum bend angle=34°. While the other 2 dipoles, EHAT:MB4 and EHBT:MB5B, shall be slightly different design: maximum B-field strength= 0.74 Tesla, and maximum bend angle=30°.
- The standard insertion length of BPM's shall be 12 cm, except where space considerations dictate the use of buttons of length 5.7 cm.
- The maximum allowed insertion length of XY-correctors shall be 7.0 cm (to mitigate interference of the slowly falling dipole field with neighbor quadrupoles).
- The raster magnets shall reach an integrated field strength up to 1.2 kG-cm.

- The overall emittance growth shall be smaller than 1% due to intrinsic aberrations of quadrupoles and dipoles, accordingly the beam emittance at output shall be $\leq 6.06\,\mu$m (r.m.s., normalized).

5 Implementation and Overall Layout

5.1 Ambient Magnetic Field and Orbit Robustness

In comparison with protons of similar energy, the electron beam is not magnetically rigid: for 75 MeV electrons, $B\rho = 0.25$ T-m, equivalent to only 3 MeV protons. This implies that the TRIUMF cyclotron's stray field is a concern. In this regard, we require that any beam displacement from the axis due to the stray field be less than the beam size. We shall use mu-metal magnetic shielding wrapped around exposed beam pipe sections to get the stray field down to 100 milliGauss [11], thus the average beta function is $\beta_{cs} = 3$ m.

In order to make the beam line optics robust to any stray field and perturbations, our design strategy is as follows: As basic building block of the beam line complex, we choose 90° FODO cell. With a phase advance per cell being $\mu = \pi/2$, the formula $\beta_{cs} = L_c/\mu$ gives a cell length of $L_c \simeq 4$ m.

While for the bend sections, we configure them to be achromatic so as to be able to handle failure modes such as drifting beam energy.

5.2 Easy to Tune

To allow easy tuning, we shall fully take advantage of the periodicity and symmetry of the optics. For the ~ 25 m long periodic channel, it is essential that beam gets well matched through. To that end, we shall put 3 profile monitors in the same location in each of the first 3 FODO cells, to exploit the beam match. Once matched there, then the entire periodic section is matched, and the subsequent bend sections can always work out nicely without having to be re-tuned. As for the tuning quadrupoles for the match, we shall configure as few as 4.

Over each bend section, we shall place profile monitors and BPM's at symmetrical locations, allowing to easily monitor and tune for the optical symmetry.

5.3 Easy to Maintain

To facilitate easy access for elements repair, replacement or maintenance, we shall try to avoid placing moving mechanical parts inside the concrete walls or shielding. In the e-hall dogleg section which is extremely congested, we shall use in-dipole correctors to save space.

5.4 Overall Layout

The EHBT layout was projected to be a long tunnel transport preceded by the e-hall dogleg to bring electrons over from e-linac axis, and succeeded by a vertical dogleg to elevate electrons by $3'$ to the same level as protons, and then followed by symmetric bends to direct beam to either target. In sequence, they are e-hall dogleg section, match and N-S periodic section, vertical dogleg section, $2 \times 34^\circ$ horizontal bend section, $2 \times 22^\circ$ horizontal dogleg section, and match section onto the target. Fig. 1 shows the overall layout in plan view.

6 E-Hall Dogleg Section

The challenges with this section are: (1) before this section there is too little space to match to the EHAT beam; (2) the bend angle and the section length is constrained; (3) the elevation has to descend by $1'$; (4) aside from the right bend to EHBT, electrons have to left bend to the EHDT. In view of these, our solution is that we defer betatron matching downstream of the dogleg; and we choose to separate the vertical bend from the horizontal one, instead of rolling the whole dogleg by an angle, to achieve the required $1'$ dip down. In this way, the dogleg can share with EHDT one dipole plus one quadrupole doublet on the e-linac axis, thus conserve space and make the beam-line layout more rational; and also the transverse coupling doesn't occur. The price to pay, however, is that the dipole may have to be built wider horizontally to accommodate both the right bend to EHBT and the left bend to EHDT.

The horizontal bend angle is compromised to be 26°. A smaller bend angle for a longer section would enable to lower strengths of the quads in between and therefore increase the dynamic apertures [12]. But the local building support structure keeps us from bending less than 26°. Vertically, the bend angle is only $\sim 6.7^\circ$; this can be accomplished with a small magnet.

In principle, we only need 4 quadrupoles, mirror-symmetrically placed, to achieve achromaticity in both x and y planes. But the constrained section length leads to a large beta-function in the quadrupoles, causing significant decrease in the dynamic aperture. To fix this, we end up adding one quad and placing it in the mid-way of the section.

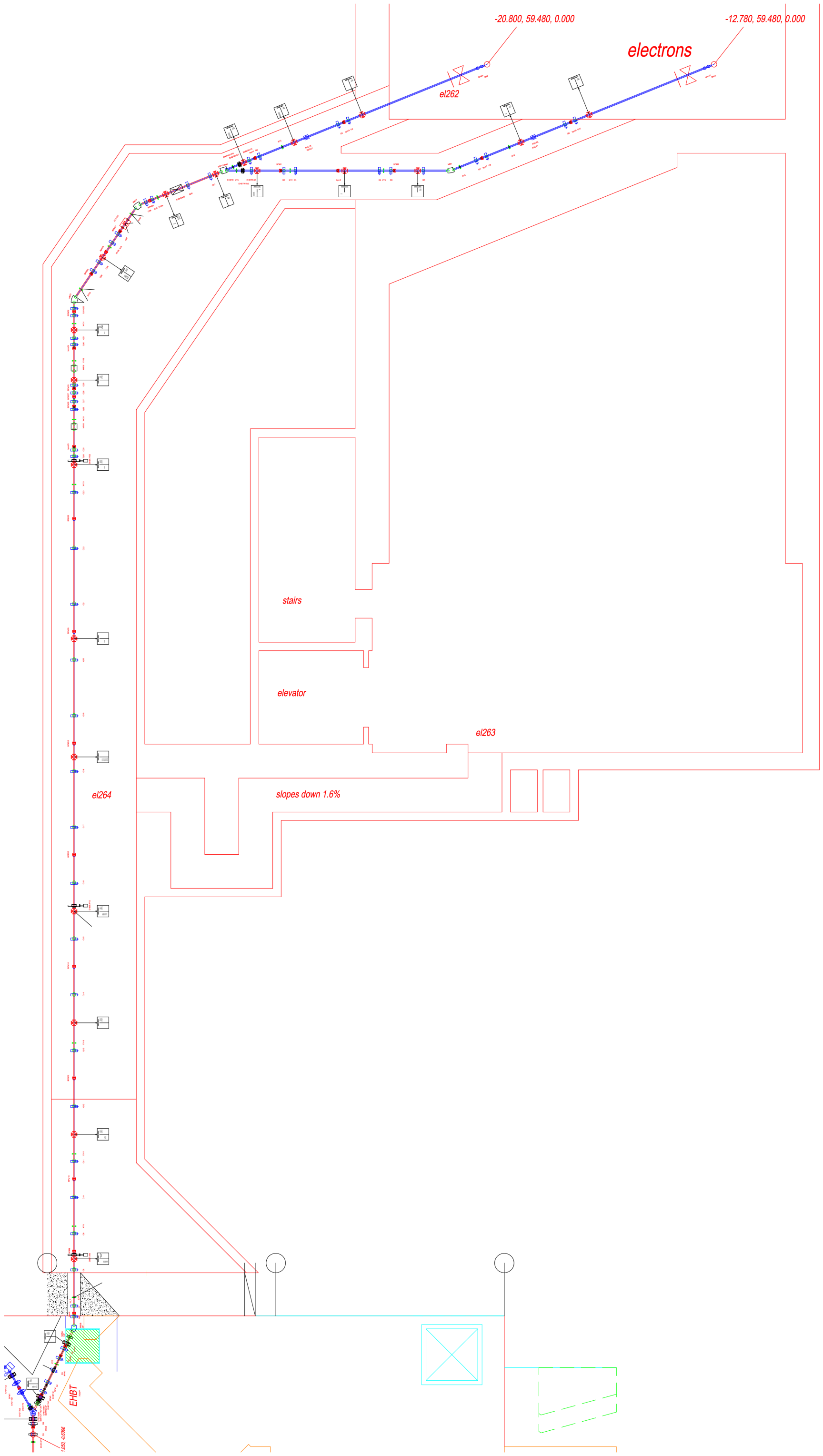

Figure 1: Plan view of EHBT layout. This diagram is for illustrative purposes.

An interesting feature with this section is that by simply reversing the polarities of the symmetrical 4 quads, we can switch the optics from a low momentum resolution mode to a high mode in the x plane. (By momentum resolution, here is defined as the ratio of dispersion to the 2× r.m.s. beam size.) In either mode, these quads are fixed of strengths, regardless of incoming beam Twiss parameters. **This shall require polarity reversal for the quadrupoles Q1,Q2,Q4,Q5, as shown in Figs. 2 and 3. The polarity reversal is very important for these quads to demagnetize when for instance the beamline is to switch from a high energy run to a low energy run, otherwise the achromaticity is jeopardized and the dispersion propagates all the way to the target.**

The doublet preceding the 1st horizontal bender serves to control the beam size over the section, while the doublet after the 2nd horizontal bender can help match with the periodic section that follows, depending on the incoming Twiss parameters; they are not superfluous. In terms of the e-linac quads survey result [13], the hysteresis effects in the magnets can cause a deviation in field integrated strength up to ±35 Gauss from the nominal value. Such a big field error in these quads can cause a mismatch of 40% throughout the beamline. This is not acceptable. **Thus, polarity reversal is also required for these quads to demagnetize, namely EHAT: Q3,Q4 and EHBT:Q6,Q7.**

Figs. 2 and 3 show the betatron beam size and momentum dispersion under the 2 tuning modes, with the baseline incoming Twiss parameters. The high resolution mode at 75 MeV will yield an orbit displacement of 2.6 times the betatron amplitude in x. This can be useful for the diagnosis of momentum tail.

It must be pointed out that β_x reaches 47.8 m at maximum (see Fig.2) while the quad's integrated strength is also high, i.e. 1.08 Tesla; these result in a very small dynamic aperture. This, due to the 3rd order intrinsic aberration in the quad, gives an emittance growth [12] of 25% assuming a misalignment of 6 mm. This is apparently too large, unacceptable, suggesting that we shall impose a stringent alignment constraint, that is, below 1 mm, at locations of these quadrupoles. As for the beam size, even if we have an emittance of 4 times larger than the expected value, the intrinsic-aberration-caused growth stays below 0.05% everywhere. The growth in total over the entire EHBT is less than 0.5%. This meets the goal of 1%.

6.1 BPM Placements

We shall put BPM in symmetrical locations and as close as possible to the quadrupoles where the beta-function is large and/or the quadrupole's integrated strength is high. Initially, we proposed to put a BPM in the mid-way of the section (i.e. in the mid-way of EHBT:Q3) so this BPM would be an in-quad strip-line. However, the in-quad strip-line was finally abandoned; instead, a solution of 2 BPM's was accepted on either side of EHBT:Q3. They are BPM2 and BPM3, symmetrically placed around Q3. We could expect to monitor any shift in beam momentum above 5×10^{-4} as the local dispersion is only ∼10 cm while the BPM's resolution [7] is around 50 μm. Provided the momentum drift of beam from the

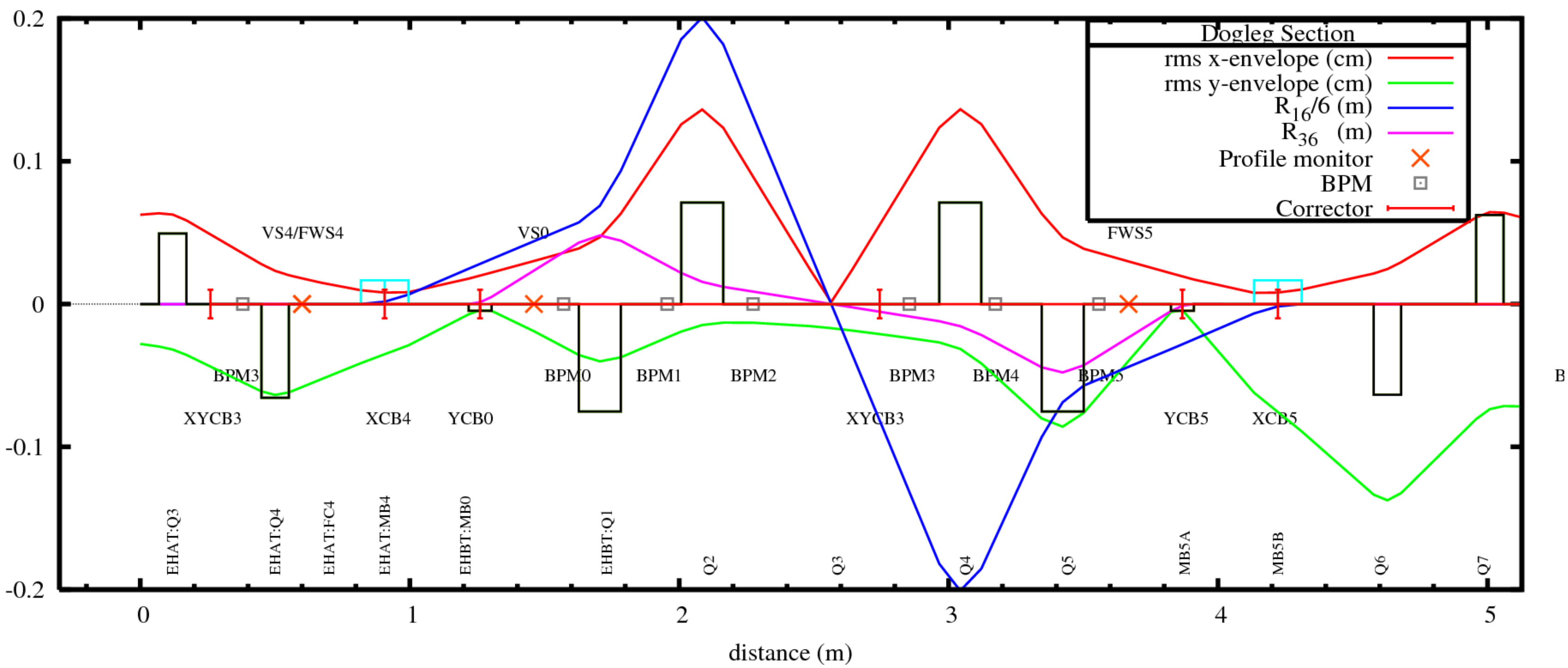

Figure 2: Beam envelope and dispersion over the dogleg section, under the high momentum resolution mode in the x plane, with the baseline incoming Twiss parameters: $\alpha_x = -2.28$, $\beta_x = 9.24\,\mathrm{m}$; $\alpha_y = -1.57$, $\beta_y = 1.74\,\mathrm{m}$.

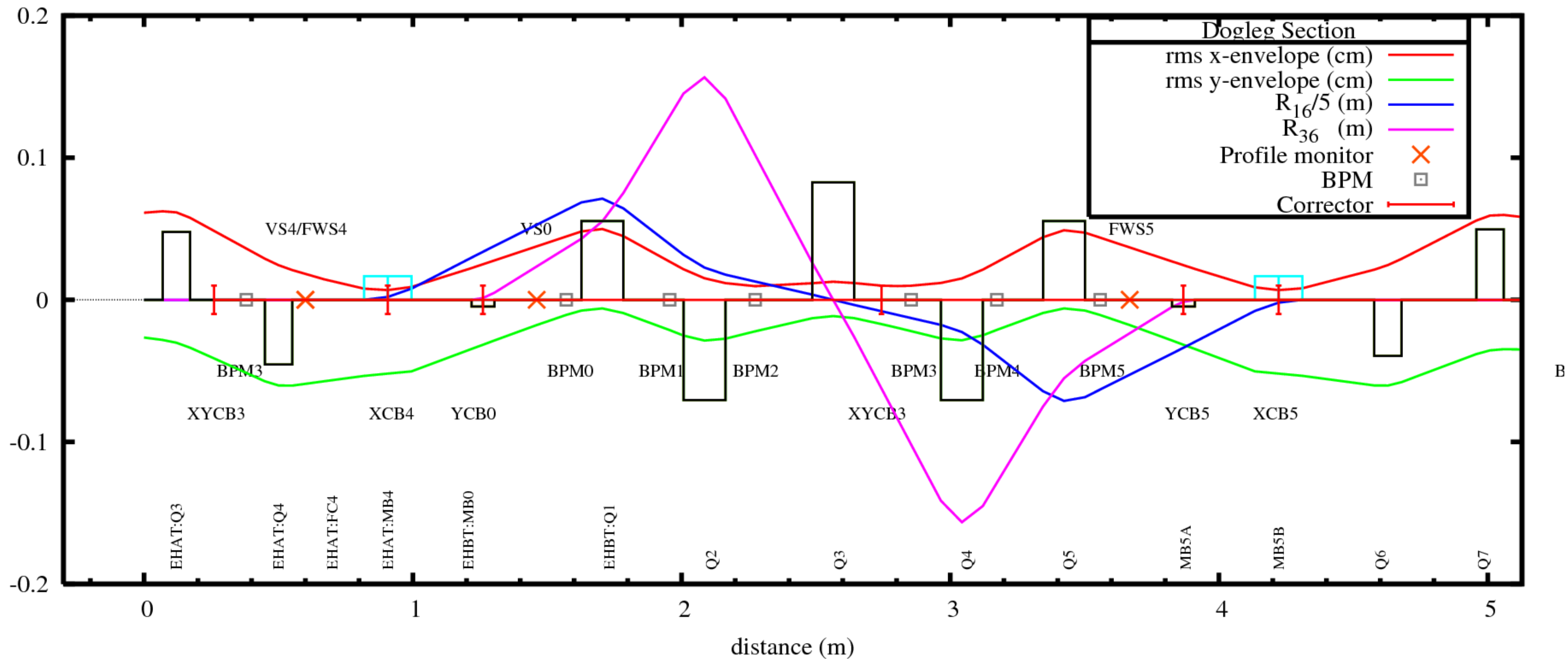

Figure 3: Beam envelope and dispersion over the dogleg section, under the low momentum resolution mode in the x plane, with the baseline incoming Twiss parameters. The resolution is 200 at location of 1.5 m.

e-linac is 2×10^{-3} (rms), we shall need a stability of 10^{-4} (rms) for the dogleg dipole's power supply, in order to allow to distinguish orbit drift caused by the dipole power supply instability.

Also, BPM0 and BPM5 shall be placed symmetrically and as close as possible to Q1 and Q5 respectively; BPM1 and BPM4 shall be placed symmetrically and as close as possible to Q2 and Q4 respectively. EHAT:BPM3 shall be placed close to EHAT:Q4. BPM7 shall be put between Q7 and Q8 [9].

Contrary to what's shown in Fig. 1, the gate valve EHBT:IV0 has been moved immediately downstream of EHBT:Q1.

6.2 Correctors

EHAT:XYCB3 shall be placed between EHAT:Q3 and EHAT:Q4. For saving space, EHAT:XCB4 and EHBT:XCB5 shall be in-dipole horizontal correctors, while YCB0 and YCB5 shall be in-dipole vertical correctors. These correctors shall have the same strength as the regular ones, which is 500 G-cm at maximum. XYCB3 shall be between Q3 and BPM3. The simulation result [16] shows that with such configuration of the correctors, plus the BPM placements as stated above, we could expect to correct the orbit errors to $\leq$1.2 mm throughout this section.

The integrated strength for the dipoles EHAT:MB4 and EHBT:MB5B is 114.3 kG-cm at 75 MeV. Relative to this dipole field, the full field needed for the correction is $500/114.3 \times 10^{-3} = 4.4 \times 10^{-3}$. While for the vertical two dipoles EHBT:MB0 and MB5A, the full field needed for the correction is $500/29.5 \times 10^{-3} = 1.7 \times 10^{-2}$. From the power supply point of view, a better solution is to place additional coils to the main dipoles so that the dipole doublet has 3 power supplies, 1 main plus 2 trims.

6.3 Profile Monitors

We shall need EHAT:VS4, placed between EHAT:Q4 and EHAT:MB4, to find out the incoming Twiss parameters by using the quadrupole scan technique. VS0 and FWS5 shall be symmetrically placed, allowing to measure the optical symmetry. All these monitors are located outside the shielding wall for easy access.

6.4 Faraday Cups

EHAT:FC4 shall be a 100 W device, serving as a beam stop when we commission or tune the beamline upstream.

As well, EHBT:FC8 shall be a 100 W device for measuring the transmission at low intensity. It shall serve as a beam stop when we commission and tune the dogleg as we do not want to spill any beam down to the tunnel.

7 N-S Periodic Section and Matching

The periodic FODO lattice shall have 90° phase advance per cell. The β-function is 3.0 m on average and the beam size is $\sim$1.0 mm at 75 MeV.

The challenge is that the periodic section must be well matched with various incoming Twiss parameters. Our solution is that we configure a matching section preceding the periodic channel; this matching section is composed of 4 quads, and these quads have to be optically orthogonal under the given incoming beam parameters. This is extremely important because it allows to achieve a good match. As long as the beam gets well matched with the periodic section, it can match through the rest of beam line nicely.

It turns out that for any of these 4 matching quads, a change of 44 Gauss in the integrated strength ($\sim$ 2% of the nominal field) can cause a beam size modulation larger than the matched size by a factor of $\sim$1.15. (By modulation is meant looking at the same location of each cell of the entire periodic section.) This is the maximum acceptable mismatch factor: within this range of variation, there is no need to tune the downstream quadrupoles. This specifies the upper limit of quadrupole's sensitivity.

Figs. 4 and 5 show the beam match through the periodic section.

7.1 BPM Placements

We shall need one BPM per 90° phase advance, namely per FODO cell. Specifically, these are BPM8, BPM10, BPM12, BPM14, BPM16, BPM18 and BPM20, separately placed in the mid-way between the adjacent 2 quads.

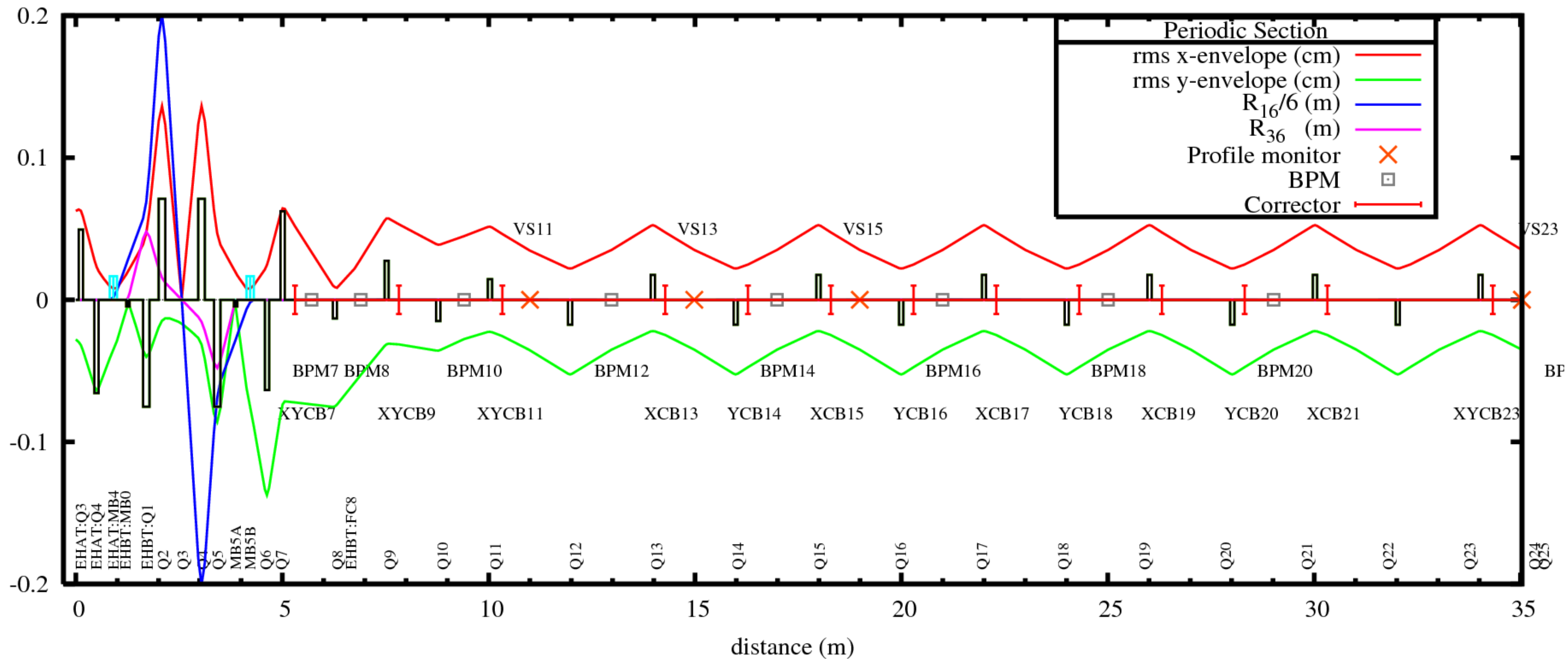

Figure 4: Beam match through the periodic section, under the high momentum resolution mode.

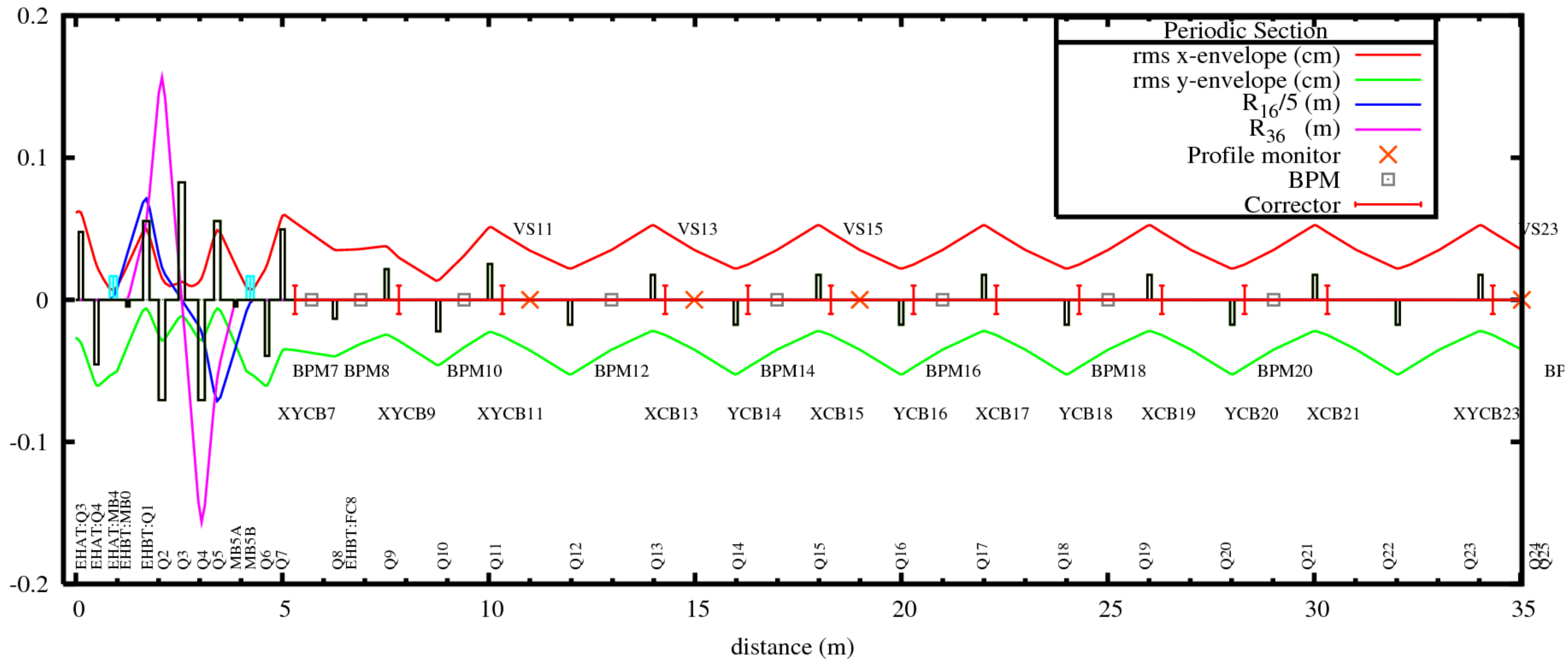

Figure 5: Beam match through the periodic section, under the low momentum resolution mode.

7.2 Correctors

We shall need one pair per 2 quads for the match section, which are XYCB7, XYCB9 and XYCB11. In the periodic channel, we shall have XCB13, XCB15, XCB17, XCB19, XCB21, and YCB14, YCB16, YCB18, YCB20. These are based on the simulation predictions [16].

7.3 Profile Monitors

We shall need at least 3 profile monitors to exploit the match. They are VS11, VS13 and VS15. They shall be placed at exactly the same location of the cell where they locate, preferably in the mid-way.

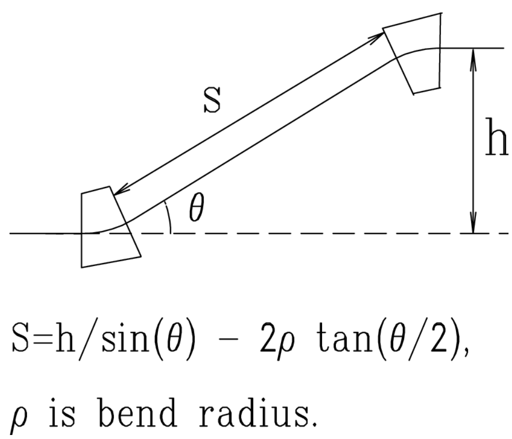

Figure 6: Schematic diagram showing a vertical dogleg. Given the elevation h, the space S between the 2 dipoles depends on the bend angle θ and bend radius ρ. The $\rho\tan(\theta/2)$ is the sagitta of dipole. Clearly, the larger the ρ and/or the θ values, the smaller the space S available.

8 Vertical Dogleg Section

The vertical dogleg section needs to bring electrons upward by $3'$. And, the bend angle is required not to far depart from $30°$. These constrain the space available between the 2 dipoles (see diagram Fig. 6), in which we expect to put in 4 quadrupoles. This is the challenge.

Optics calculations show that

- With $\rho = 75\,\mathrm{cm}$, if $\theta \geq 24°$, then $S \leq 1.9\,\mathrm{m}$. This results in an effective gap of $4.5\,\mathrm{cm}$ between the neighboring quads, which is too small to fit quads in physically.

- With $\rho = 50\,\text{cm}$, $\theta \geq 24°$ gives $S \leq 2.0\,\text{m}$ and quad's separation $\leq 13\,\text{cm}$.
- With $\rho = 35\,\text{cm}$, $\theta \geq 24°$ gives $S \leq 2.1\,\text{m}$ and quad's separation $\leq 21\,\text{cm}$.

It is uncertain that a 13 cm hard-edge-to-hard-edge space (the physical length will be even shorter) will be sufficient for diagnostic devices, but we presume 21 cm will be. Thus, we proposed a bend radius of 35 cm and applied it to all the dipoles of EHBT. This allows to minimize the number of magnet types.

Fig. 7 shows the resulting beam envelope and dispersion. The inner 2 knobs make the whole bend section achromatic and control the dispersion magnitude in between. At maximum the dispersion is only $D_y = 0.26\,\text{m}$, producing an orbit displacement of $y = D_y \cdot \Delta p/p = 0.8\,\text{mm}$ for the extreme particle. This is good enough as it is even smaller than the 2× r.m.s. betatron amplitude.

For the same reason as in the e-hall dogleg section, it shall require polarity reversal for the quads Q26,Q27,Q28,Q29 to demagnetize, otherwise a ±35 Gauss error in the field due to the hysteresis effect will ruin the tune.

8.1 BPM Placements

We shall need 5 BPM's. BPM27 is located in the middle of the section. BPM26 and BPM28 are exactly symmetrical and as close as possible to Q26 and Q29 respectively. BPM25 and BPM29 are exactly symmetrical too, and as close as possible to Q25 and Q29.

8.2 Correctors

We shall need one pair per 2 quads. Since the room between Q27 and Q28 is too tight to fit in any corrector, we shall have to miss one there and have only 3 for this section. They are XYCB23, XYCB25 and XYCB29.

8.3 Profile Monitors

We shall have 3 profile monitors. VS23 are VS31 are symmetrically placed at the beginning and end of this section. FWS29 shall be put as close as possible to Q29 where the momentum dispersion reaches maximum.

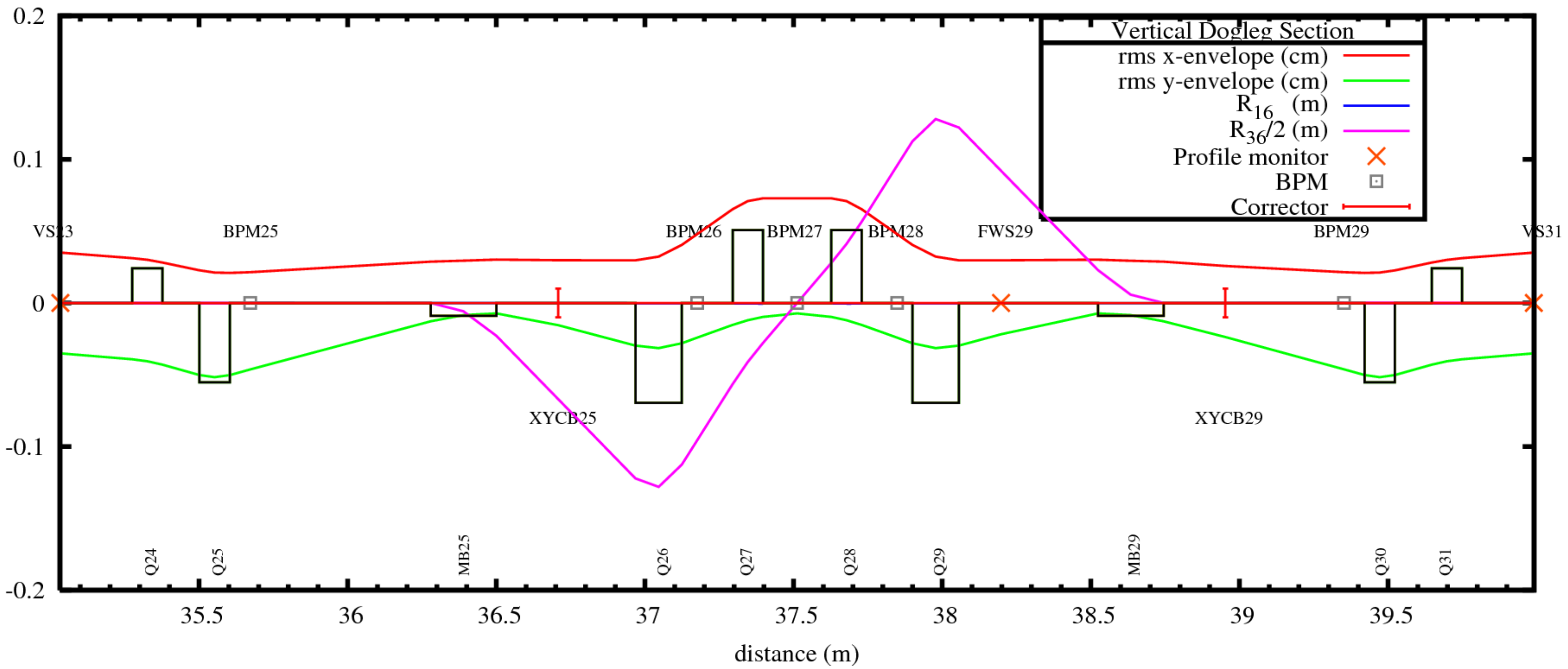

Figure 7: Beam envelope and dispersion in the vertical dogleg section.

9 $2 \times 34^\circ$ Horizontal Bend Section

Fig. 8 shows the beam envelope and dispersion. The maximum dispersion is 0.78 m. The dipole MB33 has been identified as the preferred location for implementing synchrotron-radiation-based beam diagnostic devices. The vacuum pipe chamber at the dipole shall require an extra port for the extracted photons and vacuum pipe for photon transport to a detector.

It shall require polarity reversal for the quads Q34,Q35,Q36,Q37 to demagnetize.

9.1 BPM Placements

We shall need 5 BPM's. BPM35 shall be put in the middle of the section. BPM33 and BPM37 shall be exactly symmetrical and as close as possible to Q34 and Q37 respectively. BPM32 and BPM38 shall be symmetrical too, respectively placed in the mid-way between neighboring 2 quads.

9.2 Correctors

We shall need one pair per 2 quads. They are XYCB31, XYCB33, XYCB34, XYCB37 and XYCB39.

9.3 Profile Monitors

We shall have 2. FWS35 shall be placed as close as possible to the middle of the section. VS39 shall be at the terminus of this section, in fact being symmetrical with the upstream VS31.

9.4 DCCT and Faraday Cup

Because the DCCT shall possess 40 cm space and stay free from influence of any stray field from the neighboring magnets, we shall put it between Q37 and MB37 where there is enough room available.

FC31 is a 100 W device for measuring the transmission at low intensity. It shall serve as a beam stop when we commission and tune this section. We shall put it in a separate box from

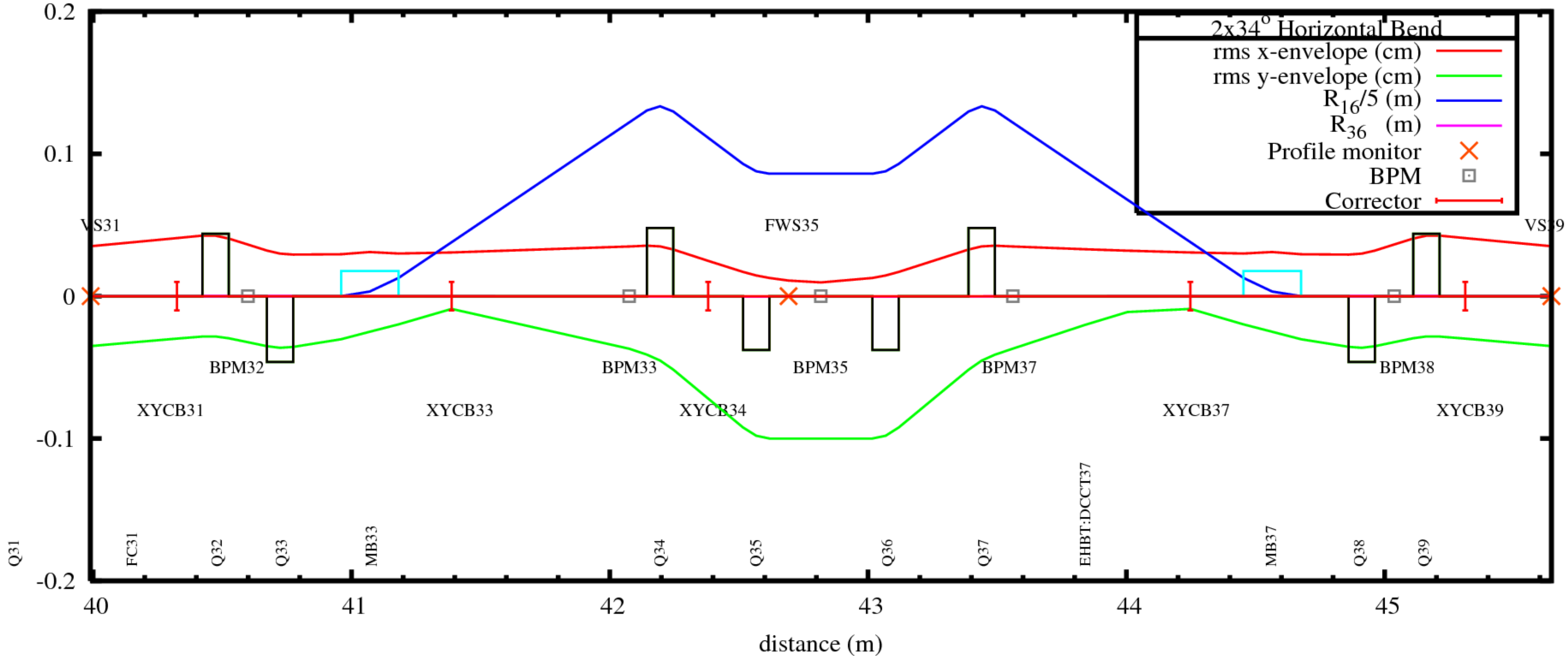

Figure 8: Beam envelope and dispersion in the $2 \times 34°$ bend section.

VS31, somewhere between VS31 and Q32. So, even if it's inserted to intercept the beam, we can still see the beam and receive beam's information from VS31. This shall be useful for the beam line commissioning and tuning.

10 $2 \times 22^\circ$ Horizontal Dogleg Section

After exiting out of the $2\times34^\circ$ horizontal bend section, the electron beam is straight delivered to the West station and/or transported to the East station through a $2 \times 22^\circ$ dogleg. We put a FODO cell between the kicker and the septum magnet. The phase advance in between is less than 90° as the cell length is shorter, only $\sim$1.8 m. Maybe this is enough. We estimate as follows: the R-matrix element R_{12} is 2.1 mm/mrad, so we only need a kick of 5 mrad to create an orbit displacement up to $0.9\,\text{mm}\times1.94\times2\times2+3.0\,\text{mm}=10\,\text{mm}$, where the 0.9 mm is the local beam size (2× r.m.s.) at 75 MeV, multiplying 1.94 gives the 2× r.m.s. size at the lowest energy 20 MeV, multiplying 2 represents the 4× r.m.s. size (with this, the loss fraction is in the order of 10^{-5} for gaussian beam), the last multiplication is accounting for the full beam size, plus 3.0 mm to account for the septum sheet thickness (here it's assumed to be 2.0 mm) plus 1.0 mm tolerance. Still, we will need to make simulations to determine the septum location and beam losses.

A beam timing pick-up may be needed for synchronizing beam pulsing with the kicker magnet firing.

If it's decided from higher level not to use kicker and septum magnet [8], then we can replace the septum magnet with a dipole magnet, This magnet shall be serving as a switching magnet and must be symmetrical with the downstream dipole EHBTE:MB6. They shall be the same design as the upstream 34° bending magnet.

We place 3 knobs (i.e. 6 quads) between the dipoles; the inner-most one is free for adjusting the beam size in between. See Fig. 9. **It shall require polarity reversal for these 6 quads, namely EHBTE:Q1,Q2,Q3,Q4,Q5,Q6.**

10.1 BPM Placements

We shall need 3 BPM's. EHBTE:BPM3 shall be put in the middle of the section; BPM1 and BPM5 shall be exactly symmetrical and as close as possible to Q2 and Q5 respectively.

10.2 Correctors

We shall need one pair per 2 quads. They are EHBTE:XYCB0, XYCB2 and XYCB4.

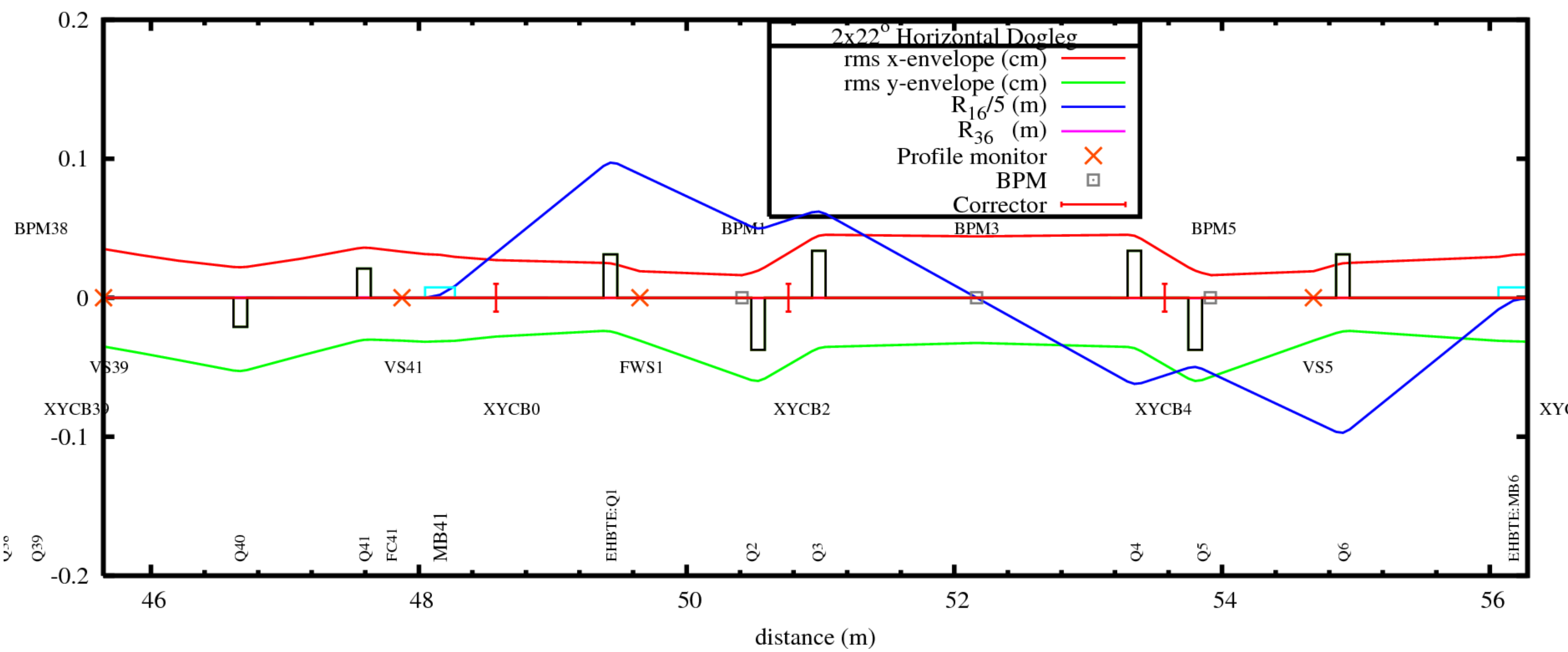

Figure 9: Beam envelope and dispersion in the $2 \times 22°$ horizontal dogleg section.

10.3 Profile Monitors

We shall have 3. VS41 shall be placed between Q41 and MB41. If needed, we shall use it with the quad scan technique to determine the ellipse of beam before going down to either leg. EHBTE:FWS1 and VS5 shall be symmetrically placed wrt the mid-point and as close as possible to EHBTE:Q1 and EHBTE:Q6 respectively.

10.4 Faraday Cup

FC41 is a 100 W device for measuring the transmission at low intensity. It shall serve as a beam stop when we commission and tune the upstream section. We shall put it in the same box as VS41.

11 Rastering onto Target

The minimum distance as required for shielding between the last magnetic element (quadrupole) and the target shall be 5.2 m, upstream from which there shall be 4.7 m space available for quadrupoles and raster magnets.

We assume that we shall use fast raster magnets with integrated strength up to 1.2 kG-cm [15]. Such a magnet can generate a deflection of 4.76 mrad for 75 MeV. To produce a spot of 20 mm diameter on the target, we shall need R-matrix elements R_{12},R_{34} to be $\geq$2.1 m. With the given separations, we can easily achieve such a magnitude, but we cannot achieve the point-to-parallel condition in the same time.

The point-to-parallel condition is important for example if particles penetrate far into a long narrow target. But, so far, it is unknown whether this will be the case. So, for the moment, we simply configure 2 doublets in front of the target, and put the raster magnets in between. Accordingly, the lever arm between the raster magnets and the target arrives at: $R_{12} = 6.2$ m and $R_{34} = 3.6$ m. These are adequate.

Figs. 10 and 11 show the intrinsic beam envelope of 1 mm (FWHM) onto the targets. Moreover, by tuning the doublets, the beam size is flexible and variable up to 3 mm. Alternatively, we can place the raster magnets downstream from the last doublet, so the lever arm stays constant and independent on any beam size changes.

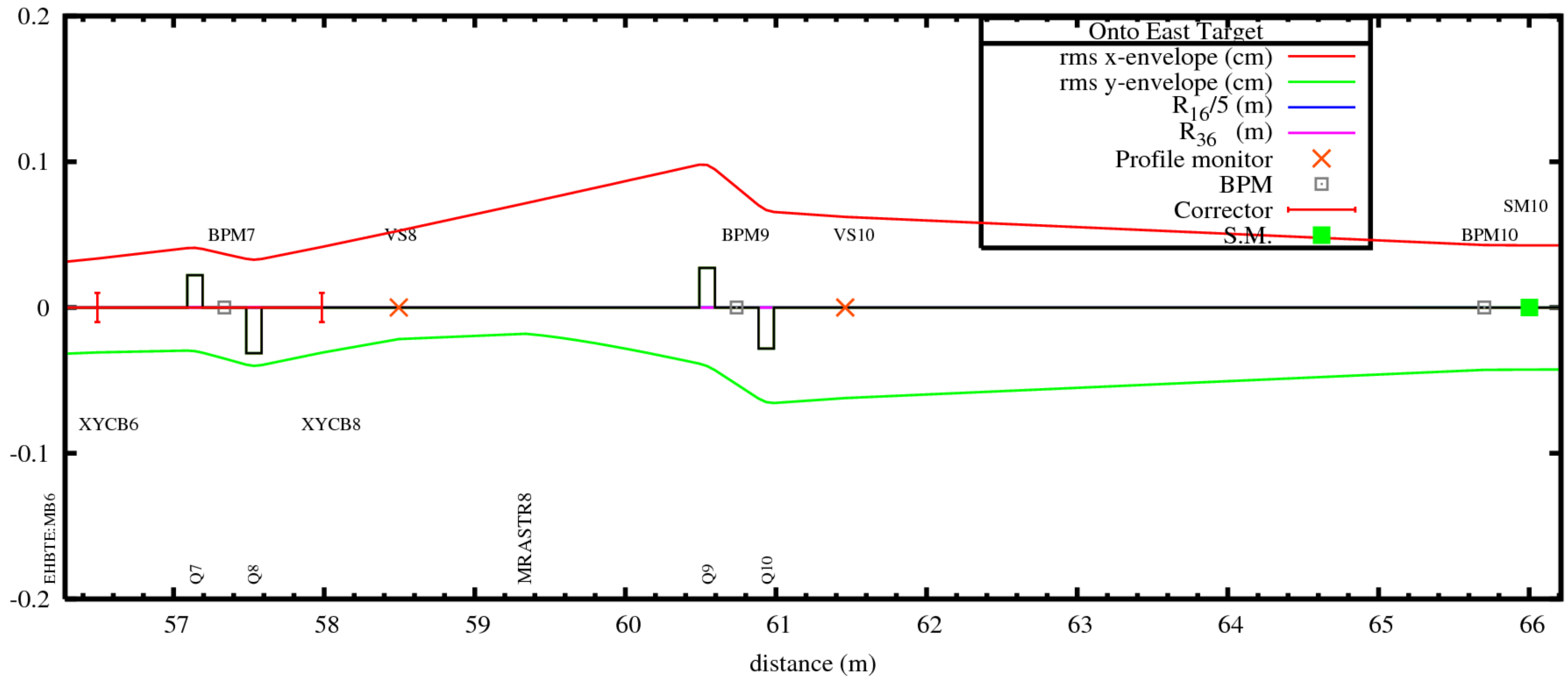

Figure 10: Beam of natural size onto the East target.

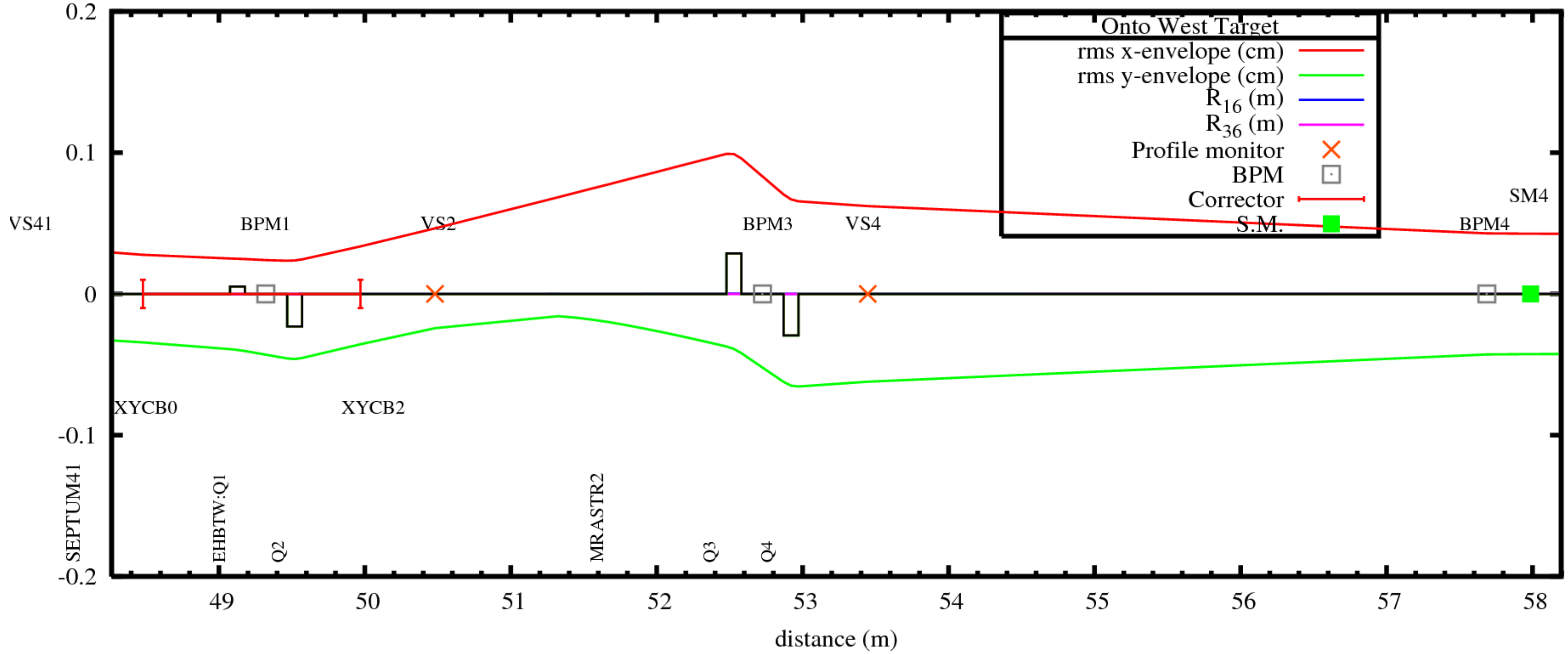

Figure 11: Beam of natural size onto the West target.

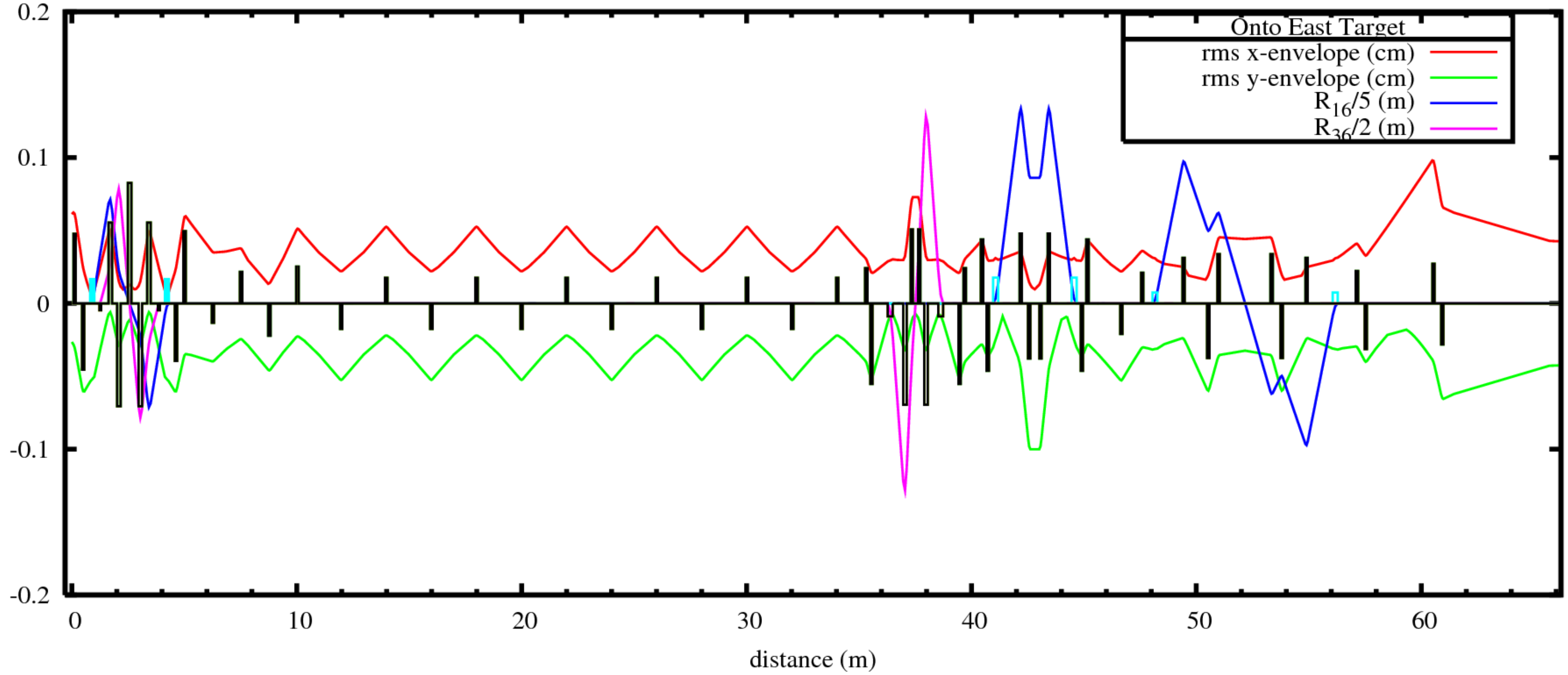

Figure 12: Beam envelope and dispersion along the full beam line up to the East target.

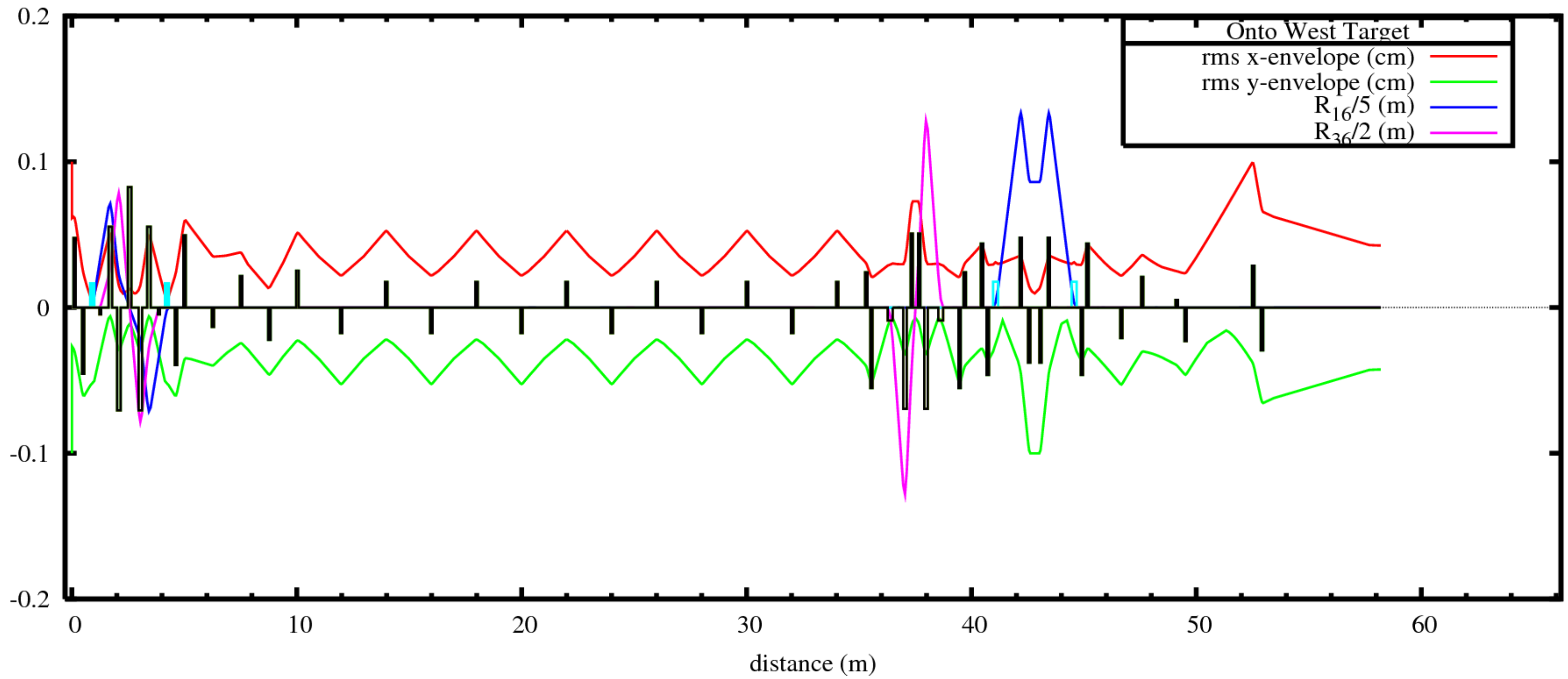

Figure 13: Beam envelope and dispersion along the full beam line up to the West target.

11.1 BPM Placements

We shall need 3 BPM's for each leg. In the East leg, BPM7 shall be in the mid-way between Q7 and Q8, BPM9 shall be in the mid-way of Q9 and Q10, while BPM10 shall be as close as possible to the target. In the West leg, BPM1 shall be in the mid-way between Q1 and Q2, BPM3 shall be in the mid-way of Q3 and Q4, while BPM4 shall be as close as possible to the target.

11.2 Correctors

We shall have 2 pairs for each leg: XYCB6 and XYCB8 in the East; XYCB0 and XYCB2 in the West.

11.3 Profile Monitors

We shall have 2 for each leg: VS8 and VS10 in the East; VS2 and VS4 in the West.

In addition, we shall need a special monitor placed as close as possible to each target, SM10 for the East and SM4 for the West, to measure the beam halo and/or transverse density distribution.

Figs. 12 and 13 show the envelope and dispersion for the full beam line up to the East and West targets.

12 Analysis of Orbit Diagnosis and Correction

Chao's analysis [16] shows that with the baseline magnitude of all types errors (including the magnetic element alignment error, element excitation error, ambient field effects, and BPM offset error), the BPM and corrector configuration specified above can provide sufficiently conservative coverage of EHBT orbit correction to keep the orbit error below $\sim 1.5\,\mathrm{mm}$ everywhere.

13 Magnetic Element List

The table that follows lists, in sequence, the coordinates of magnetic elements, including dipoles and quadrupoles, for both the West and East legs.

edge or yFCE is either the entrance or exit of a dipole (hard edge model).

MBx means a dipole. For each dipole, I give the entrance, mid-point and exit along the reference trajectory; I also give the cross-over point (CoP) and bend angle. The cross-over point is the point where the axis of the incoming beam and the axis of outgoing beam intersect. All the dipoles are rectangular shape.

Dipoles of the same bend angles are powered in series with a single power supply.

Qx means a quadrupole. For each quadrupole, I give the mid-point.

The 3rd column specifies the polarity of quadrupoles.

The 4th column is the reference trajectory length in meter. The x, y and z coordinates are such that +x points to East, +y points to North, +z points upward. The origin is cyclotron centre.

As for the quadrupole's latitude on the drawing, I specify 0 mm for EHBT:Q3, +/-5 mm for Q1 and Q5 (any movement must be symmetrical), also +/-5 mm for Q2 and Q4 (movement must be symmetrical too), and +/-10 mm for the others (movement must be symmetrical). As for the installation tolerances, I specify 0.15 mm for the transverse and 1.0 mm for the longitudinal.

Location	Name	Pol.	s[m]	x[m]	y[m]	z[m]	Bend Angle[degr]
EHAT	Q3	F	0.12000	-36.84700	11.05000	-0.60960	
	Q4	D	0.50000	-36.84700	11.43000	-0.60960	
	edge		0.81870	-36.84700	11.74870	-0.60960	
	MB4		0.90678	-36.83705	11.83603	-0.60960	26
	CoP			-36.84700	11.83833	-0.60960	
	edge		0.99486	-36.80771	11.91888	-0.60960	
EHBT	yFCE		1.21856	-36.70965	12.11994	-0.60960	
	MB0		1.26097	-36.69107	12.15803	-0.61084	6.7146
	CoP			-36.69104	12.15810	-0.60960	
	yFCE		1.30338	-36.67255	12.19600	-0.61456	
	Q1	F	1.70538	-36.49753	12.55484	-0.66157	
	Q2	D	2.08538	-36.33209	12.89404	-0.70600	
	Q3	F	2.56433	-36.12358	13.32156	-0.76200	
	Q4	D	3.04328	-35.91506	13.74908	-0.81800	
	Q5	F	3.42328	-35.74962	14.08828	-0.86243	
	yFCE		3.82528	-35.57460	14.44712	-0.90944	
	MB5A		3.86769	-35.55609	14.48509	-0.91316	6.7146
	CoP			-35.55612	14.48502	-0.91440	

yFCE		3.91010	-35.53751	14.52318	-0.91440	
edge		4.13380	-35.43944	14.72424	-0.91440	
MB5B		4.22188	-35.41010	14.80709	-0.91440	26
CoP			-35.40015	14.80479	-0.91440	
edge		4.30997	-35.40015	14.89442	-0.91440	
Q6	D	4.62866	-35.40015	15.21312	-0.91440	
Q7	F	5.00866	-35.40015	15.59312	-0.91440	
Q8	D	6.27466	-35.40015	16.85912	-0.91440	
Q9	F	7.52666	-35.40015	18.11112	-0.91440	
Q10	D	8.77866	-35.40015	19.36312	-0.91440	
Q11	F	10.03066	-35.40015	20.61512	-0.91440	
Q12	D	11.97422	-35.40015	22.55868	-0.91440	
Q13	F	13.97936	-35.40015	24.56381	-0.91440	
Q14	D	15.98449	-35.40015	26.56895	-0.91440	
Q15	F	17.98962	-35.40015	28.57408	-0.91440	
Q16	D	19.99475	-35.40015	30.57921	-0.91440	
Q17	F	21.99988	-35.40015	32.58434	-0.91440	
Q18	D	24.00502	-35.40015	34.58947	-0.91440	
Q19	F	26.01015	-35.40015	36.59460	-0.91440	
Q20	D	28.01528	-35.40015	38.59974	-0.91440	
Q21	F	30.02041	-35.40015	40.60487	-0.91440	
Q22	D	32.02554	-35.40015	42.61000	-0.91440	
Q23	F	34.03067	-35.40015	44.61513	-0.91440	
Q24	F	35.32624	-35.40015	45.91070	-0.91440	
Q25	D	35.55224	-35.40015	46.13670	-0.91440	
yFCE		36.27878	-35.40015	46.86324	-0.91440	
MB25		36.38950	-35.40015	46.97315	-0.90285	24
CoP			-35.40015	46.97561	-0.91440	
yFCE		36.50021	-35.40015	47.07825	-0.86870	
Q26	D	37.04575	-35.40015	47.57663	-0.64681	
Q27	F	37.34575	-35.40015	47.85069	-0.52479	
Q28	F	37.67809	-35.40015	48.15429	-0.38961	
Q29	D	37.97809	-35.40015	48.42836	-0.26759	
yFCE		38.52363	-35.40015	48.92673	-0.04570	
MB29		38.63434	-35.40015	49.03184	-0.01155	24
CoP			-35.40015	49.02939	0.00000	
yFCE		38.74506	-35.40015	49.14175	0.00000	
Q30	D	39.47160	-35.40015	49.86829	0.00000	
Q31	F	39.69760	-35.40015	50.09429	0.00000	
Q32	F	40.47420	-35.40015	50.87089	0.00000	
Q33	D	40.72420	-35.40015	51.12089	0.00000	
edge		40.95964	-35.40015	51.35633	0.00000	
MB33		41.07118	-35.38373	51.46624	0.00000	34
CoP			-35.40015	51.47130	0.00000	
edge		41.18272	-35.33588	51.56654	0.00000	

	Q34	F	42.19515	-34.76974	52.40588	0.00000	
	Q35	D	42.56715	-34.56172	52.71428	0.00000	
	Q36	D	43.06842	-34.28142	53.12985	0.00000	
	Q37	F	43.44042	-34.07340	53.43825	0.00000	
	edge		44.45286	-33.50725	54.27759	0.00000	
	MB37		44.56440	-33.43217	54.35952	0.00000	34
	CoP			-33.44298	54.37290	0.00000	
	edge		44.67594	-33.33641	54.41592	0.00000	
	Q38	D	44.91138	-33.11812	54.50412	0.00000	
	Q39	F	45.16138	-32.88633	54.59777	0.00000	
	Q40	D	46.66670	-31.49062	55.16168	0.00000	
	Q41	F	47.59015	-30.63442	55.50760	0.00000	
	edge		48.04742	-30.21044	55.67891	0.00000	
	MB41		48.15801	-30.10456	55.71027	0.00000	22
	CoP			-30.10665	55.72085	0.00000	
	edge		48.26860	-29.99465	55.72085	0.00000	
EHBTE	Q1	F	49.43116	-28.83210	55.72085	0.00000	
	Q2	D	50.53415	-27.72910	55.72085	0.00000	
	Q3	F	50.98816	-27.27510	55.72085	0.00000	
	Q4	F	53.34511	-24.91814	55.72085	0.00000	
	Q5	D	53.79912	-24.46415	55.72085	0.00000	
	Q6	F	54.90211	-23.36114	55.72085	0.00000	
	edge		56.06467	-22.19859	55.72085	0.00000	
	MB6		56.17526	-22.08868	55.73143	0.00000	22
	CoP			-22.08663	55.72085	0.00000	
	edge		56.28585	-21.98281	55.76279	0.00000	
	Q7	F	57.14201	-21.18900	56.08352	0.00000	
	Q8	D	57.53401	-20.82554	56.23036	0.00000	
	Q9	F	60.54343	-18.03527	57.35772	0.00000	
	Q10	D	60.93543	-17.67182	57.50456	0.00000	
EHBTW	Q1	F	49.12750	-29.20900	56.08351	0.00000	
	Q2	D	49.51951	-28.84555	56.23036	0.00000	
	Q3	F	52.52893	-26.05528	57.35772	0.00000	
	Q4	D	52.92093	-25.69183	57.50456	0.00000	

The table that follows lists the nominal strengths of quadrupoles at 75 MeV, and the information on how they shall be powered, and the information on the power supplies, where the circuit current and voltage values were calculated in terms of the preliminary design [17, 18, 19] for ARIEL quadrupole magnets.

Proposed Power Supplies

Note: The 2nd column specifies which quads are run as singlets (1), or doublets (2) or strings (12) in series with a single ps.

Name/location	Quad's Quantity	Int. Strength (Tesla)	Circuit Current (A)	Circuit Voltage (V)	Max.Allowed PS's Ripple (half of peak to peak) (mA)
EHBT					
E-hall Dogleg Section					
EHAT:Q3	1	0.4845	38.57	3.22	102.2
EHAT:Q4	1	0.4773	37.99	3.17	100.7
EHBT: Q1,Q5	2	0.8232	65.03	10.85	156.1
EHBT: Q2,Q4	2	1.0234	80.85	13.49	493.2
EHBT:Q3	1	1.0478	82.78	6.91	2516.4
EHBT:Q6	1	0.4055	32.03	2.67	99.3
EHBT:Q7	1	0.5195	41.04	3.42	110.8
Matching Section					
EHBT:Q8	1	0.1356	3.00	3.31	42.5
EHBT:Q9	1	0.1277	2.82	3.12	99.3
EHBT:Q10	1	0.1672	3.70	4.08	63.8
EHBT:Q11	1	0.2136	17.00	1.42	152.2
N-S Periodic Section					
EHBT:Q12-Q23	12	0.1838	4.06	53.82	41.2
2x24 degr. Vertical Dogleg					
EHBT: Q24,Q31	2	0.3029	24.11	4.02	248.3
EHBT: Q25,Q30	2	0.5791	45.75	7.63	139.5
EHBT: Q26,Q29	2	1.0455	82.59	13.78	536.9
EHBT: Q27,Q28	2	0.5084	40.16	6.70	112.5
2x34 degr. Hori. Bend					
EHBT: Q32,Q39	2	0.3004	23.91	3.99	218.8
EHBT: Q33,Q38	2	0.2932	23.34	3.89	312.8
EHBT: Q34,Q37	2	0.4708	37.48	6.25	146.2
EHBT: Q35,Q36	2	0.3823	30.43	5.08	65.4
Single FODO Cell					
EHBT:Q40	1	0.2103	16.74	1.40	165.7
EHBT:Q41	1	0.2103	16.74	1.40	357.4
2x22 degr. Hori. Dogleg					
EHBTE: Q1,Q6	2	0.3507	27.92	4.66	502.6
EHBTE: Q2,Q5	2	0.3845	30.61	5.11	87.2
EHBTE: Q3,Q4	2	0.3616	28.78	4.80	159.7
Matching to Target Stations					
EHBTE:Q7	1	0.0712	1.57	1.74	71.8
EHBTE:Q8	1	0.0735	1.62	1.79	67.1
EHBTE:Q9	1	0.2352	18.72	1.56	49.6
EHBTE:Q10	1	0.2290	18.23	1.52	93.0
EHBTW:Q1	1	0.0600	1.33	1.46	51.9
EHBTW:Q2	1	0.1281	2.83	3.13	36.9
EHBTW:Q3	1	0.2369	18.85	1.57	66.0
EHBTW:Q4	1	0.2396	19.07	1.59	101.1

14 Diagnostic Element List

The table below lists, in sequence, the coordinates of correctors and diagnostic elements including AC current transformer (ACCT), BPM's, view screens, fast wire scanners, Faraday cups, and DCCT.

```
For each element listed below, I give the mid-point coordinate. The 3rd
column s is the reference trajectory length in meter.

The x, y and z coordinates are in meter. The label 1* in the last column
means phase 1 deferred but we will put them in later.

The latitude on drawing are as following: 0 mm for the EHBT:BPM27, BPM35,
EHBTE:BPM3, VS23, VS31 and VS39; +/- 2 cm for the other BPM's and profile
monitors (any movement must be symmetrical wherever the optical symmetry
dictates); +/- 10 cm for the DCCT and correctors. The installation
tolerances are 0.15 mm transverse and 1.0 mm longitudinal.
```

Location	Name	s[m]	x[m]	y[m]	z[m]	Phase
EHAT	ACCT2	-0.30000	-36.8470	10.75000	-0.60960	1
	XCB3	0.26000	-36.84700	11.19000	-0.60960	1
	YCB3	0.26000	-36.84700	11.19000	-0.60960	1
	BPM3	0.38000	-36.84700	11.31000	-0.60960	1
	VS4	0.60000	-36.84700	11.53000	-0.60960	1
	FWS4	0.60000	-36.84700	11.53000	-0.60960	1
	FC4	0.67000	-36.84700	11.60000	-0.60960	1
	XCB4	0.90678	-36.83705	11.83603	-0.60960	1
EHBT	YCB0	1.26097	-36.69107	12.15803	-0.61084	1
	VS0	1.46092	-36.60396	12.33662	-0.63299	1
	BPM0	1.57092	-36.55607	12.43481	-0.64585	1
	BPM1	1.95538	-36.38869	12.77799	-0.69080	1
	BPM2	2.27433	-36.24983	13.06270	-0.72809	1
	XCB3	2.74381	-36.04544	13.48176	-0.78299	1
	YCB3	2.74381	-36.04544	13.48176	-0.78299	1
	BPM3	2.85433	-35.99732	13.58042	-0.79591	1
	BPM4	3.17328	-35.85846	13.86513	-0.83320	1
	BPM5	3.55774	-35.69108	14.20831	-0.87815	1
	FWS5	3.66774	-35.64319	14.30650	-0.89102	1
	YCB5	3.86769	-35.55609	14.48509	-0.91316	1
	XCB5	4.22188	-35.41010	14.80709	-0.91440	1
	XCB7	5.30866	-35.40015	15.89312	-0.91440	1
	YCB7	5.30866	-35.40015	15.89312	-0.91440	1
	BPM7	5.70866	-35.40015	16.09312	-0.91440	1

FC8	6.83566	-35.40015	17.42012	-0.91440	1
BPM8	6.98566	-35.40015	17.57012	-0.91440	1
XCB9	7.82666	-35.40015	18.41112	-0.91440	1
YCB9	7.82666	-35.40015	18.41112	-0.91440	1
BPM10	9.40466	-35.40015	19.98912	-0.91440	1
XCB11	10.33066	-35.40015	20.91512	-0.91440	1
YCB11	10.33066	-35.40015	20.91512	-0.91440	1
VS11	10.77405	-35.40015	21.35851	-0.91440	1*
BPM12	12.97679	-35.40015	23.56125	-0.91440	1
XCB13	14.27936	-35.40015	24.86381	-0.91440	1
VS13	14.78431	-35.40015	25.36877	-0.91440	1*
YCB14	16.28449	-35.40015	26.86895	-0.91440	1
BPM14	16.98705	-35.40015	27.57151	-0.91440	1
XCB15	18.28962	-35.40015	28.87408	-0.91440	1
VS15	18.79458	-35.40015	29.37903	-0.91440	1*
YCB16	20.29475	-35.40015	30.87921	-0.91440	1
BPM16	20.99732	-35.40015	31.58178	-0.91440	1
XCB17	22.29988	-35.40015	32.88434	-0.91440	1
YCB18	24.30501	-35.40015	34.88947	-0.91440	1
BPM18	25.00758	-35.40015	35.59204	-0.91440	1
XCB19	26.31015	-35.40015	36.89460	-0.91440	1
YCB20	28.31528	-35.40015	38.89974	-0.91440	1
BPM20	29.01784	-35.40015	39.60230	-0.91440	1
XCB21	30.32041	-35.40015	40.90487	-0.91440	1
XCB23	34.33067	-35.40015	44.91513	-0.91440	1
YCB23	34.33067	-35.40015	44.91513	-0.91440	1
VS23	35.03324	-35.40015	45.61770	-0.91440	1*
BPM25	35.67224	-35.40015	46.25670	-0.91440	1
XCB25	36.70785	-35.40015	47.26794	-0.78424	1
YCB25	36.70785	-35.40015	47.26794	-0.78424	1
BPM26	37.17575	-35.40015	47.69539	-0.59393	1
BPM27	37.51192	-35.40015	48.00249	-0.45720	1
BPM28	37.84809	-35.40015	48.30960	-0.32047	1
FWS29	38.19809	-35.40015	48.62934	-0.17811	1
XCB29	38.95269	-35.40015	49.34938	0.00000	1
YCB29	38.95269	-35.40015	49.34938	0.00000	1
BPM29	39.35160	-35.40015	49.74829	0.00000	1
VS31	39.99060	-35.40015	50.38729	0.00000	1*
FC31	40.13060	-35.40015	50.52729	0.00000	1
XCB31	40.32420	-35.40015	50.72089	0.00000	1
YCB31	40.32420	-35.40015	50.72089	0.00000	1
BPM32	40.59920	-35.40015	50.99589	0.00000	1
XCB33	41.38778	-35.22121	51.73655	0.00000	1
YCB33	41.38778	-35.22121	51.73655	0.00000	1
BPM33	42.07515	-34.83684	52.30640	0.00000	1

	XCB34	42.38115	-34.66573	52.56008	0.00000	1
	YCB34	42.38115	-34.66573	52.56008	0.00000	1
	FWS35	42.71247	-34.48046	52.83476	0.00000	1*
	BPM35	42.81779	-34.42157	52.92207	0.00000	1
	BPM37	43.56042	-34.00629	53.53773	0.00000	1
	DCCT37	43.84042	-33.84972	53.76986	0.00000	1*
	XCB37	44.24779	-33.62192	54.10758	0.00000	1
	YCB37	44.24779	-33.62192	54.10758	0.00000	1
	BPM38	45.03638	-33.00222	54.55095	0.00000	1
	XCB39	45.31138	-32.74725	54.65397	0.00000	1
	YCB39	45.31138	-32.74725	54.65397	0.00000	1
	VS39	45.64498	-32.43794	54.77894	0.00000	1*
	VS41	47.87415	-30.37109	55.61399	0.00000	1*
	FC41	47.87415	-30.37109	55.61399	0.00000	1
EHBTE	XCB0	48.57664	-29.68662	55.72085	0.00000	1
	YCB0	48.57664	-29.68662	55.72085	0.00000	1
	FWS1	49.65116	-28.61210	55.72085	0.00000	1*
	BPM1	50.41416	-27.84910	55.72085	0.00000	1
	XCB2	50.76116	-27.50210	55.72085	0.00000	1
	YCB2	50.76116	-27.50210	55.72085	0.00000	1
	BPM3	52.16664	-26.09662	55.72085	0.00000	1
	XCB4	53.57211	-24.69114	55.72085	0.00000	1
	YCB4	53.57211	-24.69114	55.72085	0.00000	1
	BPM5	53.91912	-24.34415	55.72085	0.00000	1
	VS5	54.68211	-23.58114	55.72085	0.00000	1*
	XCB6	56.49520	-21.78870	55.84122	0.00000	1
	YCB6	56.49520	-21.78870	55.84122	0.00000	1
	BPM7	57.33801	-21.00727	56.15694	0.00000	1
	XCB8	57.98501	-20.40738	56.39931	0.00000	1
	YCB8	57.98501	-20.40738	56.39931	0.00000	1
	VS8	58.49601	-19.93359	56.59074	0.00000	1*
	MRASTR8	59.33901	-19.15197	56.90653	0.00000	1
	BPM9	60.73943	-17.85355	57.43114	0.00000	1
	VS10	61.46043	-17.18505	57.70123	0.00000	1*
	BPM10	65.70243	-13.25193	59.29031	0.00000	1
	SM10	66.00243	-12.97378	59.40270	0.00000	1*
EHBTW	XCB0	48.48070	-29.80871	55.84122	0.00000	1
	YCB0	48.48070	-29.80871	55.84122	0.00000	1
	BPM1	49.32351	-29.02728	56.15693	0.00000	1
	XCB2	49.97051	-28.42739	56.39931	0.00000	1
	YCB2	49.97051	-28.42739	56.39931	0.00000	1
	VS2	50.48151	-27.95360	56.59073	0.00000	1*
	MRASTR2	51.32451	-27.17198	56.90653	0.00000	1

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        BPM3       52.72493 -25.87355  57.43114   0.00000    1
        VS4        53.44593 -25.20505  57.70123   0.00000    1*
        BPM4       57.68793 -21.27194  59.29031   0.00000    1
        SM4        57.98793 -20.99379  59.40270   0.00000    1*
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15 Summary

In summary, the optics design of EHBT accommodates all the known operational modes. There is enough flexibility in the optics and it is easy to tune. The magnet design parameters are credible, and the number of magnet types have been rationalized and minimized. Provisions have been considered to incorporate steering, diagnostics elements and vacuum components. Nevertheless, we are still concerned about the congestion in the e-hall dogleg section. We must move on to the engineering design as soon as possible to reconcile these elements because they matter to the optics.

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