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TRI-DN-23-17 - Dark Light Beam Optics Specifications - Design Note

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History of Changes

Release number	Date	Description of changes	Authors
1	2024–07–12	Initial release	A. Mahon T. Planche

Keywords: beam optics, beam envelope, permanent magnets, electromagnetic magnets, target scattering, steering, dispersion

Distribution List: A. Distributee1, A. Distributee2

Contents

1 Requirements

RS-1: In all high-power configurations, the 2×RMS beamsize at the center location of the EHD dump should be a minimum of 8 mm×8 mm.

Rationale: The dump was designed to be compatible with 10 kW delivery of an unrastered beam with a minimum beam size of 6 mm×6 mm RMS [1]. This number is in fact very conservative and we have demonstrated during commissioning that the beam dump can accept a 2×RMS beams sizes down to 8 mm at 10 kW [2].

RS-2: DarkLight (DL) beam optics model must be compatible with regular beam operation at the e-Linac when the scattering target is removed.

Rationale: The e-Linac will still need to perform regular beam delivery to other users and groups, so the beam optics solution detailed herein must not interfere with that.

RS-3: DL target ladder must include a scintillator screen and camera.

Rationale: A previously installed view screen has been removed from the beamline to make space for the additional elements required to run DL. Therefore a suitable replacement must be integrated into the DL setup to compensate as it is a diagnostics element required for regular beam delivery.

RS-4: Model must include a minimum of one beam position monitor (BPM) and view screen/fast wire scanner diagnostics elements downstream of the DL target.

Rationale: These are required diagnostics elements for regular beam delivery, and are additionally required to evaluate performance of the new optical elements of the model, the magnitude of scattering from the DL target and the position of beam into the dump.

RS-5: Model must include sufficient steering to center the beam on each diagnostics location.

Rationale: The magnetic fields of the DL spectrometer dipoles will steer the beam and need to be compensated accordingly.

RS-6: The 6×RMS size of the scattered beam envelope must not surpass 1 inch in both x and y plane before entering the beam dump shielding.

Rationale: This is required in order to minimize the dose seen in the hall in order to comply with safety regulations.

RS-7: Model should be valid for an energy range of 27-31 MeV.

Rationale: RF performance is typically unreliable, we should be able to operate in a circumstance where we cannot reach the desired 31 MeV.

2 Constraints

CS-1: Distance between crossover point of Dipole EHDT:MB4 and beginning of the beam dump shielding must be 227 ±1 cm.

Rationale: This is the current space available for the new optics design in the e-Hall without modifying shielding.

CS-2: Distance between crossover point of Dipole EHDT:MB4 and the beam dump entrance must be 349±1 cm.

Rationale: This is the set distance between these elements from CAD drawings which must remain unchanged.

CS-3: Distance between target and face of 1st permanent magnet quadrupole (PMQ) must be a minimum of 20 cm.

Rationale: This is to leave space for the necessary target scattering chamber for the experiment.

CS-4: Distance between target and face of 1st electromagnetic quad (EMQ) must be a minimum of 105 cm.

Rationale: This is due to the width of EM quads, if placed before they would intersect with the aforementioned spectrometer magnets.

3 Beam Optics Design

Element	Dist from X-over point (cm)	Length (cm)	Comment
Bellows	20.82		Element centre
BPM 1	25.24	3.21	Element centre
Steerer 1	14.71-30.21	2.50	Range
Chamber wall	30.21	-	Upstream edge
TARGET	45.37	1×10^{-4}	
Chamber wall	60.6	-	Downstream edge
Flange edge + screws	65.23	-	Closest point for PMQs
PMQ 1	70.56	9.30	Element centre
PMQ 2	82.57	9.30	Element centre
PMQ 3	94.58	9.30	Element centre
BPM 2	99.5 - 157.0	3.21	Range
Steerer 2	99.5 - 157.0	2.50	Range
EMQ 1	162.09	10.0	Element centre
Steerer 3	167.5 - 185.0	2.50	
BPM 3	167.5 - 185.0	3.21	
EMQ 2	190.09	10.0	Element centre
Diagnostics box	195.5 - 227.5	11.43	VS6 & FWS6
BPM 4	195.5 - 227.5	3.21	
DUMP Shielding	227.87	126.79	Upstream edge
BPM 5	227.87	3.21	
Collimator	334.7	21.27	Element centre
DUMP entrance	349.54	-	Element start
DUMP centre	410.87	122.64	Element centre
DUMP end	472.19	-	Element end

Table 1: Position of optical elements in DarkLight Beam Optics Model with respect to the crossover (X-over) point of dipole EHDT:MB4.

The DarkLight beam optics design was optimized using the envelope code TRANSOPTR [3]. The changes to the existing e-Linac beamline begin downstream of Dipole EHDT:MB4. See table 1 for detailed locations of beamline elements.

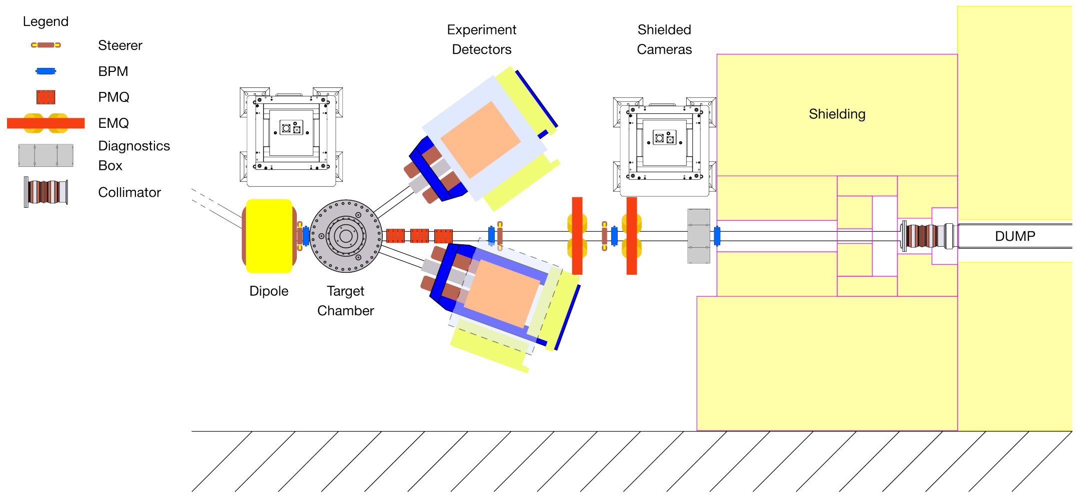

Figure 1: Sketch of DarkLight beam optics layout, with beam direction going from left to right. Not to scale. Created by S.D. Rädel.

Figure 1 shows a sketch of the new beam optics layout. A first BPM/steerer pair is located upstream of the target chamber in order to position the beam coming from the bending section onto the 1μm tantalum target. The BPM is integrated into the upstream target chamber beampipe. The steerer will be fitted around a set of bellows that will connect the upstream target chamber flange to the beampipe at the end of EHDT:MB4. The target chamber is then immediately followed by three permanent magnet quads (PMQs) to handle the initial scattering from the target. These PMQs have integrated field strengths of 0.55 T, 0.90 T and 0.55 T respectively. A second BPM/steerer pair is positioned after the last permanent magnet to qualify and steer the scattered beam. This is then followed by two standard e-Linac electromagnetic quadrupoles (EMQs) with maximum integrated strenght of 0.72 T for adjusting of the beam tune onto the dump. A third BPM/steerer pair is positioned between the EMQs for additional steering into the dump. Finally there is a diagnostic box and final BPM to qualify the beam as it enters the dump. The initial beam conditions at the location of the target used in the subsequent optimizations are presented in table 2.

x (cm)	**x' (rad)**	**y (cm)**	**y' (rad)**
0.65×10^{-1}	0.43×10^{-3}	1.3×10^{-1}	1.5×10^{-3}
1 2	0.826	**3 4**	-.997598

Table 2: Initial beam parameters at the location of the DL target: 2 RMS beam size (x & y), 2 RMS angular spread of the beam (x' & y') and corresponding correlation parameters.

The spacing of optical elements and strengths of the PMQs & EMQs were optimized in TRANSOPTR in order to best contain the beam envelope within the bounds outlined in the requirements section. Figure 2 shows the optimized beam envelope for a beam scattered on a 1 µm tantalum target for the desired energy for the experiment, 30 MeV. The scattering angles were obtained from Geant4 simulations performed by Laura Miller and Angela Sabzevari Gonzalez, and are detailed in table 3. Figures 3 and 4 shows the 2 sigma and 6 sigma envelopes obtained for the full set of energies ranging from 27-31 MeV. Note: the PMQ focal strengths will vary with beam energy, which can be compensated by changing EMQ strengths. Table 4 presents the optimized values for the two EMQs for each energy.

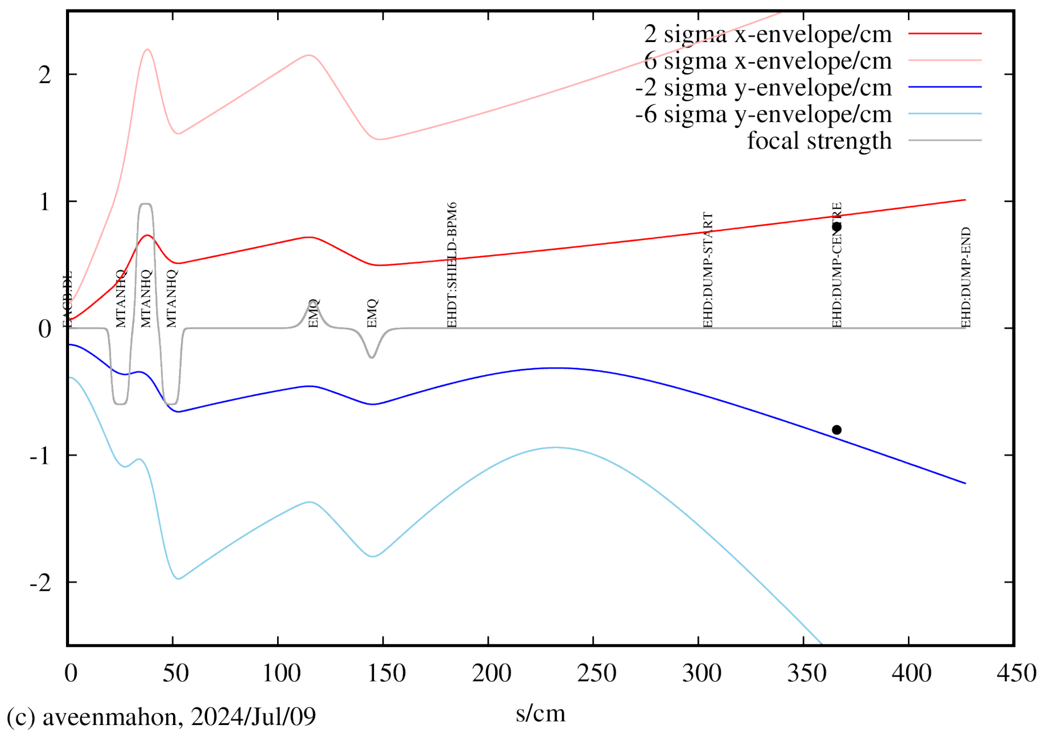

Figure 2: Beam envelopes simulated in TRANSOPTR from location of 1 µm tantalum target to beam dump for beam energy of 30 MeV.

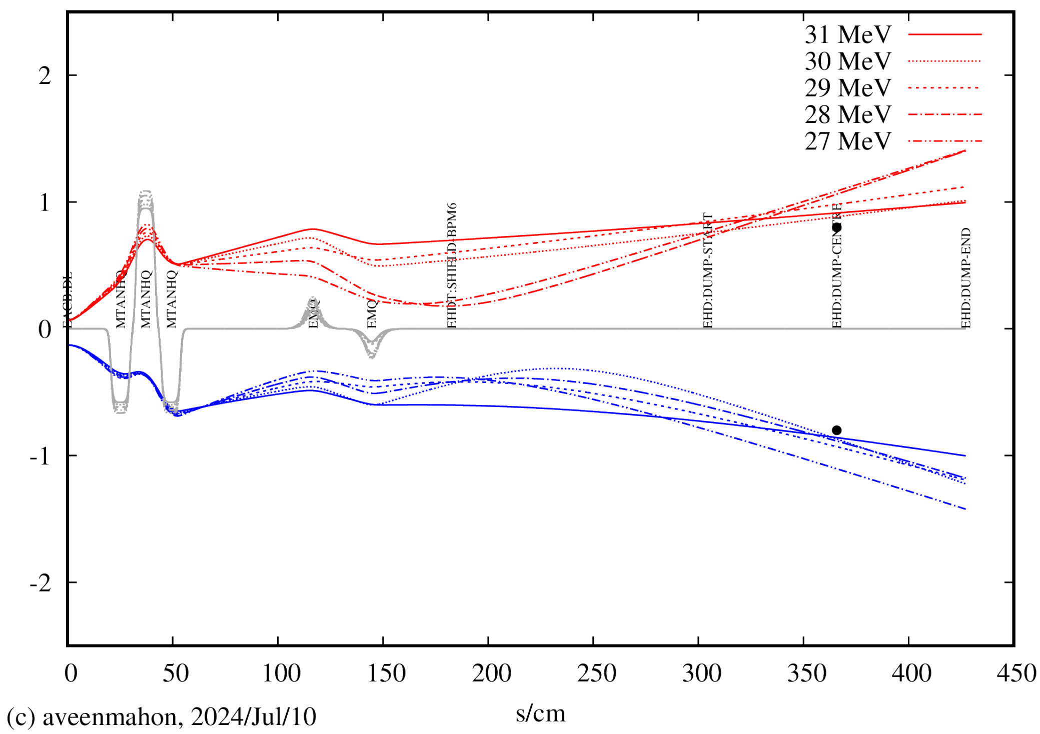

Figure 3: 2 sigma beam envelopes simulated in TRANSOPTR from location of 1 µm tantalum target to beam dump for beam energies of 27-31 MeV. Black dots are included to represents visually RS-1.

Beam Energy	RMS x (mrad)	RMS y (mrad)
27 MeV	8.01	8.01
28 MeV	7.75	7.76
29 MeV	7.51	7.52
30 MeV	7.28	7.31
31 MeV	7.05	7.11

Table 3: 1 RMS scattering angles in both x and y from Geant4 simulations for beam energies ranging from 27-31 MeV.

Beam Energy	27 MeV	28 MeV	29 MeV	30 MeV	31 MeV
EMQ1 (T)	0.15	0.20	0.10	0.18	0.13
EMQ2 (T)	-0.15	-0.18	-0.10	-0.20	-0.09

Table 4: Electromagnetic quadrupole tunes for beam optics model with 1 µm tantalum target in at various energies.

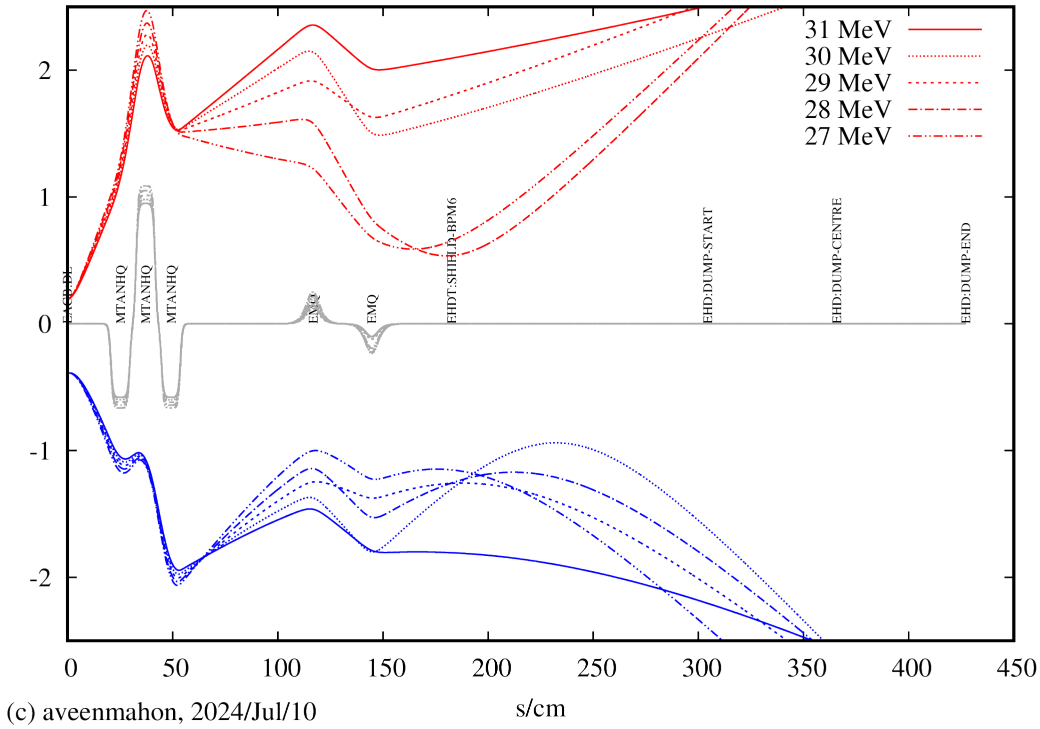

Figure 4: 6 sigma beam envelopes simulated in TRANSOPTR from location of 1 μm tantalum target to beam dump for beam energies of 27-31 MeV.

To verify RS-2, the TRANSOPTR code was run using this beam optics design without the scattering from the target. Figures 5 and 6 shows the beam envelopes obtained in this configuration for the full set of energies ranging from 27-31 MeV. Table 5 presents the set values for the two EMQs for each energy.

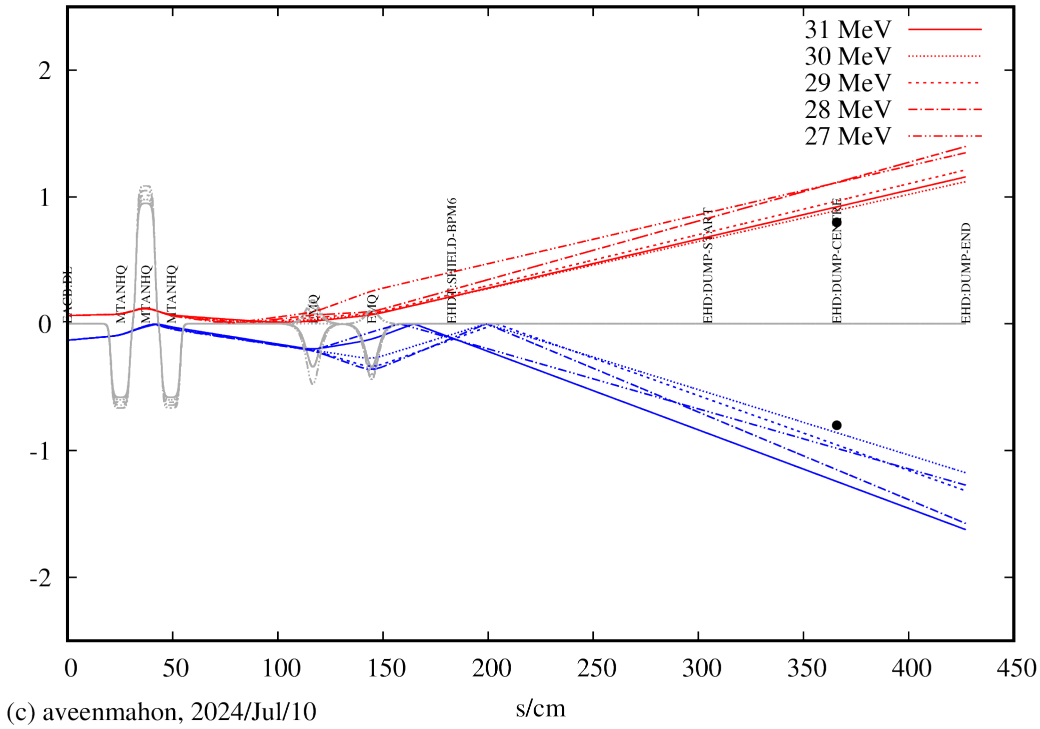

Figure 5: 2 sigma beam envelopes simulated in TRANSOPTR without scattering for beam energies of 27-31 MeV. Black dots are included to represents visually RS-1.

Beam Energy	27 MeV	28 MeV	29 MeV	30 MeV	31 MeV
EMQ1 (T)	-0.37	0.15	0.11	0.00	-0.3
EMQ2 (T)	0.08	-0.35	-0.33	-0.3	-0.3

Table 5: Electromagnetic quadrupole tunes for beam optics model with target out at various energies.

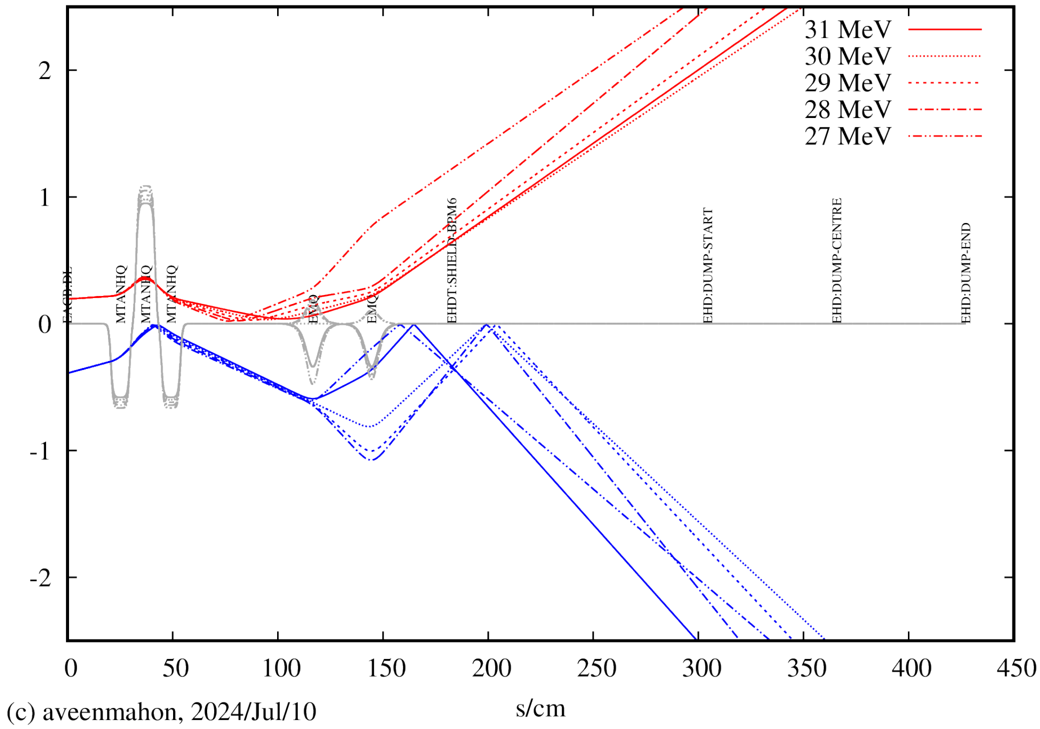

Figure 6: 6 sigma beam envelopes simulated in TRANSOPTR without scattering for beam energies of 27-31 MeV.

4 Stray magnetic field

The spectrometer magnets used in the detector system of the DarkLight experiment will emit stray magnetic fields that may affect the primary electron beam from the target to the dump. Thus additional steering considerations may be required to compensate for the effect of these stray fields on the beam envelope. These spectrometers are fixed at angles of 20 and 36 degrees respective to the beam pipe. The on axis field from each spectrometer when tuned for the nominal beam energy of 31 MeV are depicted below. Figures 7 and 8 show the three components of the field on axis for each individual spectrometer, for the case where these are operated independently one from the other. Figure 9 shows the field components for the case where both spectrometers are operated simultaneously. It is evident from these plots that the spectrometer closest to the beamline will have the dominating effect.

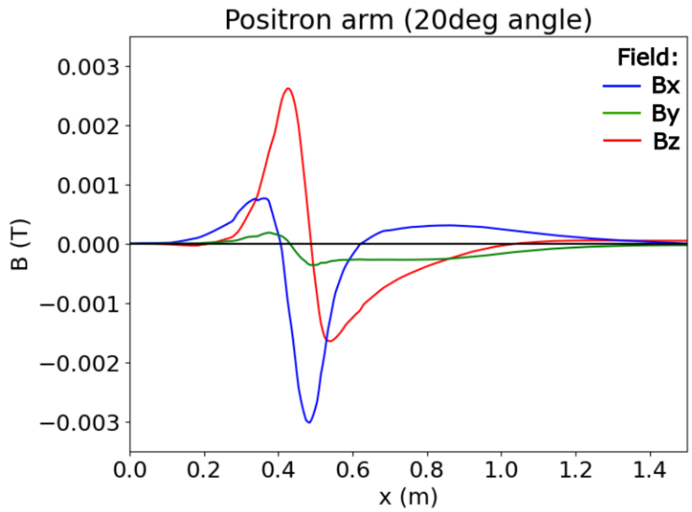

Figure 7: Stray field on-axis for spectrometer at 20 degree angle. Note: the reference frame defines x as travelling along the positive beam direction, y pointing upwards and z pointing to the right.

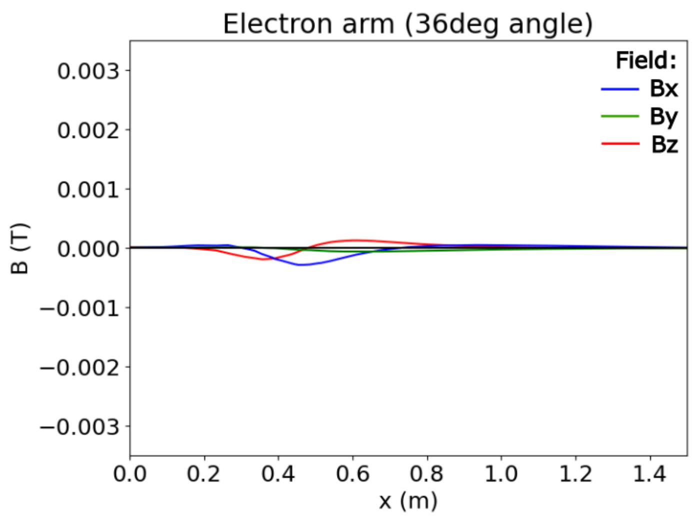

Figure 8: Stray field on-axis for spectrometer at 36 degree angle. Note: the reference frame defines x as travelling along the positive beam direction, y pointing upwards and z pointing to the right.

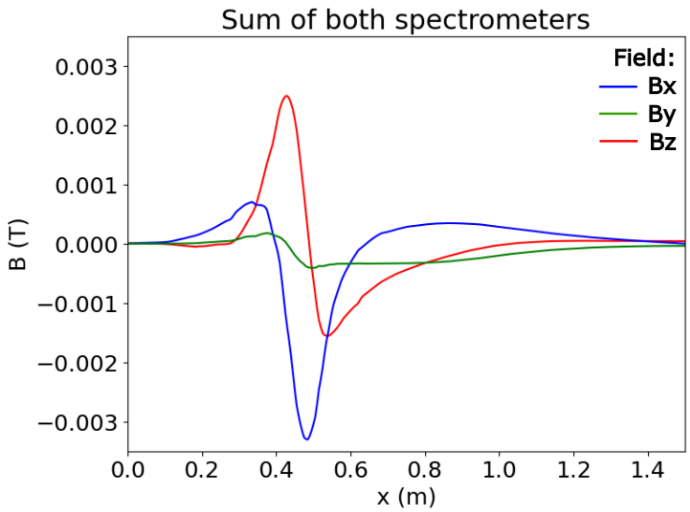

Figure 9: Stray field on-axis from both spectrometers combined. Note: the reference frame defines x as travelling along the positive beam direction, y pointing upwards and z pointing to the right.

The strength of the standard e-Linac steerers is 5 Gm; taking the integral of the transverse components of the spectrometer stray fields and comparing them to this order of magnitude will inform us whether an existing e-Linac steerer can compensate for them or not. Table 6 details the integrated field components in both transverse directions for all possible spectrometer configurations. These values inform us that the integrated field in the y direction when both spectrometers are being operated at the same time is the largest contribution, but is still below the level of 5 Gm. This implies that a standard e-Linac steerer would be sufficient to correct for this stray field.

	20°	**36°**	**20° + 36°**
y	-1.59 Gm	-0.39 Gm	-1.99 Gm
z	-0.33 Gm	-0.01 Gm	-0.34 Gm

Table 6: Integrated field components from each spectrometer configuration.

One can additionally calculate the specific deflection angle that the beam will see as a result of the stray field by dividing the integrated fields by the magnetic rigidity of the beam. This quantity can be calculated as follows:

$$B\rho = \frac{\beta\gamma mc}{q} \tag{1}$$

where for a 30 MeV electron beam ($\mathrm{m_e = 0.511 MeV/c^2,\ q = 1\,e}$):

$$\beta\gamma = \sqrt{(E_k/(m_e c^2) + 1)^2 - 1} = 59.7 \tag{2}$$

Yielding a value for $B\rho$ of 1017 Gm. Table 7 details the calculated deflection angles in both transverse directions for all spectrometer configurations.

	20°	**36°**	**20° + 36°**
y	-1.56 mrad	-0.39 mrad	-1.95 mrad
z	-0.32 mrad	-0.01 mrad	-0.33 mrad

Table 7: Deflection angles from each spectrometer configuration.

The 1 RMS scattering angle from the scattering of primary electrons on DarkLight's tantalum target is on the order of 7 mrad, which we know causes a problematic scattering effect. Comparing this value to the calculated deflection angles above, we see that the deflection angles are close to one order of magnitude lower, and should not require as extreme measures to correct.

Therefore, the addition of a standard e-Linac steerer would be sufficient to counter the effects of the stray fields from the magnetic spectrometers on the beamline. One other option would be to wrap the beamline with mu metal to shield it from the external magnetic field altogether, which may be preferable as space is a limiting constraint of this model.

References

[1] I. Earle, e-linac beam dump maximum un-rastered beam power, Tech. Rep. Document-115170, TRIUMF, https://documents.triumf.ca/docushare/dsweb/Get/Document-115170 (2015).

[2] S. Rädel, E-linac beam commissioning record - EABT/EABD and EHAT and EHDT, Tech. Rep. Document-191059, TRIUMF, https://documents.triumf.ca/docushare/dsweb/Get/Document-191059 (2015).

[3] R. Baartman, Transoptr: Changes since 1984, TRIUMF, Vancouver, Canada, Rep. TRI-BN-16-06 (2016).