

# Designing a Wien Filter Model with General Particle Tracer

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 (Dated: April 18, 2018)

The Continuous Electron Beam Accelerator Facility (CEBAF) injector employs a beamline component called a Wien filter which is typically used to select charged particles of a certain velocity. The Wien filter is also used to rotate the polarization of a beam, setting the spin of particles as they pass through. To ensure the Wien filter is functioning properly, Beam Position Monitors (BPMs) are placed before and after the filter to measure changes in the beam orbit caused by the filter. For the purpose of diagnostics, magnetic dipoles called correctors are placed at various positions upstream of the filter. The field strengths of these dipoles are varied to bend or kick the beam, affecting particle trajectories through the Wien. The focus of this project was to create a simulation of the Wien filter using General Particle Tracer (GPT). The results from these simulations were vetted against machine data to analyze the accuracy of the Wien model. Due to the close agreement between simulation and experiment, the data suggest that the Wien filter model is accurate.

## I. BACKGROUND

The Wien filter is composed of crossed electrostatic and magnetostatic fields, formed by a pair of capacitors and a magnetic dipole running transverse to the beam's direction of travel. Following the Lorentz force equation, particles in the beam travel unaffected through the filter if their velocity  $v_0$  satisfies  $-F_E = v_0 \times F_B$ , but otherwise they are deflected from the central orbit.

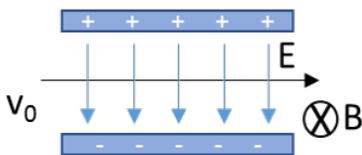


FIG. 1: Wien filter with perpendicular electric and magnetic fields.

Because the fields are balanced for a specific velocity, Wien filters are velocity selectors, and they are most often used in electron microscopy and mass separation applications to separate out specific electrons or ions in a beam by velocity [1]

The Wien filter also has the capacity to rotate the polarization of a beam [2] which is important for nuclear physics experiments studying parity violation [3]. Its large magnetic field integral causes the spin of passing particles to precess, while the compensating electric field maintains their direction of travel. CEBAF employs the Wien filter primarily for this unique ability.

To collect data on a specific beamline component, CEBAF utilizes a program called Fast Optics (Fopt). Fopt sequentially activates magnetic dipoles called correctors to bend, or "kick," the beam and records the change in the beam orbit in the BPMs. Fopt is an

automated difference orbit generation and measurement tool that can be used to characterize the effect a beam line element, such as the Wien filter, has on the beam. The Fopt corrector kicks can be simulated using GPT [4], offering a good way to systematically compare injector simulations with experiment.

Solenoids in the injector ensure the beam is focused and imaged properly between beam components, and it is important for the beam to pass through the center of each solenoid. If the beam is not centered in a solenoid, the beam samples a radial magnetic field at the entrance and exit of the solenoid resulting in a net rotation about the solenoid central axis. From operational experience, it is known that for a given Wien setting (known as Wien angle for the net change it causes in the spin orientation) the design settings for the Wien electrode voltage and dipole magnet strength do not produce perfectly balanced fields as required and deflect the beam. Therefore, each time the Wien is configured for a new Wien angle, the dipole setting is adjusted to restore the centered orbit through the solenoids. For the Wien angles studied here, the Wien dipole was adjusted accordingly before each set of Fopt measurements.

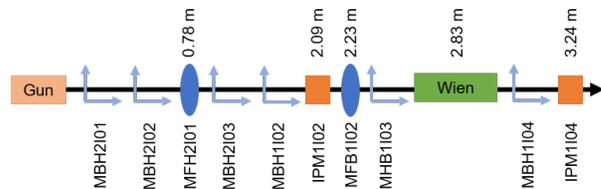


FIG. 2: Beamline section showing BPMs, correctors, and Wien filter (not to scale).

## II. METHODOLOGY

GPT was used to create models of the Wien filter. Several different models were created as GPT custom elements, each with their own functions and parameters. The first model used homogeneous, rectangular electric and magnetic fields to simulate the fields in the Wien filter. These fields were constructed in GPT using the erect and rectmagnet functions for the electric and magnetic fields, respectively. Eventually, these fields were replaced with 3D field maps, created with the finite element field solver Opera [5] [6].

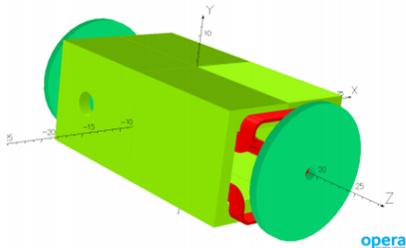


FIG. 3: Rendering of Wien filter in Opera [5]

The field map versions are far more accurate, as they closely resemble the fields actually created by the Wien filter. As opposed to the rectangular fields, the field maps have tapered edges, true to reality.

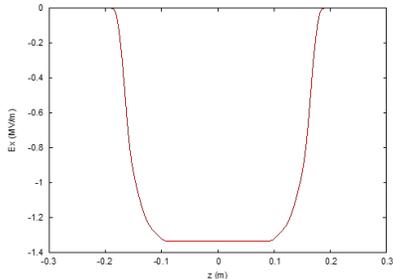


FIG. 4: on-axis electric field component

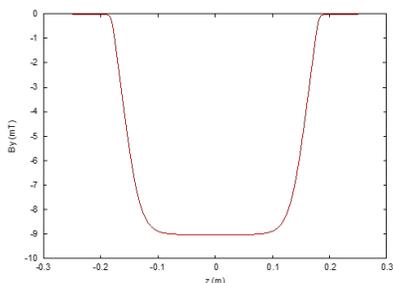


FIG. 5: on-axis magnetic field component

Figure 4 shows the x-z plane of the electric field map, while Figure 5 shows the y-z plane of the magnetic field map. On a negatively charged particle like the electron,

the electric field causes a force in the +x direction, while the magnetic field causes a force in the -x direction. Note that CEBAF uses a left-handed (LH) coordinate system where the +z-axis is in the beam propagation direction and the +x-axis points toward the interior of the accelerator racetrack (inboard). For dipole magnets bending in the horizontal plane (x-z), the convention is that a positive field strength produces a positive kick (inboard), and the corresponding field is  $B = -B_y \hat{j}$ . The Wien dipole field map and control system setpoint adhere to this convention.

For ease of use, another set of models was created which allow the user to specify the beam energy and either the electric or magnetic field. The other field is then solved for within the GPT element. This way, for example, a relativistic gamma (Lorentz factor,  $\gamma$ ) and electric field can be specified, and the magnetic field required to keep the beam on axis can be solved for. Figure 6 shows the trajectory of electrons passing through this model with the gamma specified as a Gaussian distribution with  $\sigma = 3$  centered around 80 keV.

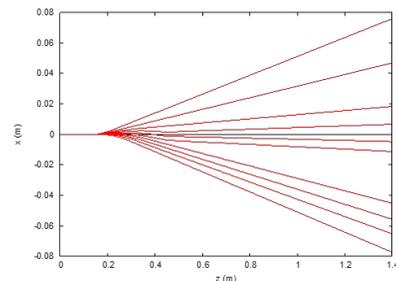


FIG. 6: Electron trajectories with  $\gamma$  distribution through field map

To collect data from the actual injector, Fopt was used to kick each corrector pair upstream of the Wien filter, in addition to one downstream corrector. Each corrector was kicked individually, and no two correctors were active simultaneously. The beam position was recorded at each of the eight BPMs up to a Faraday cup  $\approx 5$  m downstream of BPM IPM1I04. The Wien filter is located between the first two BPMs in the injector. Fopt data were collected for Wien OFF (baseline) and four angles (each requiring Wien dipole adjustments to restore the orbit as described above):  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ , and  $20^\circ$ . The corrector kicks were  $+100 \mu\text{Radian}$  and  $-100 \mu\text{Radian}$  corresponding to a  $0.129508$  G-cm magnitude change in each corrector setting. All Fopt BPM data files were translated to Self Describing Data Sets (SDDS) formatted files [7] with the left-handed x-positions converted to the right-handed coordinate system to be consistent with GPT, which uses the right-handed coordinate system.

This data was compared with simulated results to vet the Wien filter model for accuracy. A script was created that organized the GPT simulation and Fopt SDDS data files by corrector kick. The script produced the GPT input files for each kick from a template file; the

scripts to run each simulation; and plotting scripts to plot the simulation results and the Fopt data. In GPT, the generic dipole magnet element, rectmagnet, assumes  $B=+Byj$  for a positive field strength. This is opposite the CEBAF horizontal dipole convention, and the script accounted for this by changing the sign of all horizontal kicks. This script allowed for easy comparisons between GPT and Fopt data while providing documentation connecting the Fopt and associated simulation parameters and results together.

### III. RESULTS

Every corrector was kicked first in the negative direction, and then in the positive direction. Since the beam is bent further by a stronger dipole, the negative and positive kicks of the same size should be equal but opposite in size. As expected, the relationship between corrector strength and kick size is linear. Figure 6 shows that when the MHB1I03H horizontal and MHB1I03V vertical correctors are kicked in the positive and negative directions, the positive kicks are equal and opposite the negative kicks. There is also a negligible effect on the vertical beam position caused by the horizontal corrector, and vice versa. This suggests that the horizontal and vertical components of each corrector pair are completely decoupled.

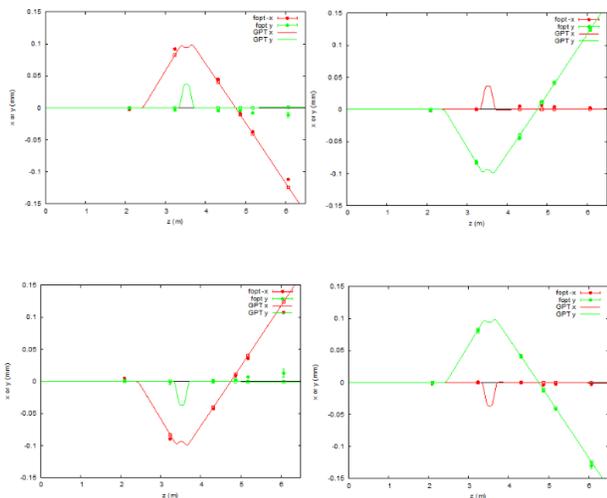


FIG. 7: from top left to bottom right: MHB1I03H Wien off, LHC negative kick (=RHC positive kick); MHB1I03V Wien off, negative kick; MHB1I03H Wien off, LHC positive kick (=RHC negative kick); MHB1I03V Wien off, positive kick

When setting the Wien angle during the Fopt measurements on the operational accelerator, a program calculated the required  $B \cdot dl$  (Gcm) and electrode voltage settings to attain that angle. These are called the design values. While the mismatch in the design fields in the

machine allowed the beam to easily propagate through the Wien, albeit with a net deflection, the design values caused erratic behavior in the GPT simulations. To mitigate this problem in the GPT simulation, for the  $15^\circ$  design settings with the beam coming into the Wien on-axis, the effective length of the Wien electrodes was adjusted to account for the tapered ends of the 31.5 cm rods. When the appropriate length (31.1485 cm) was found to reproduce the predicted design fields [5], the unperturbed orbit entering and exiting the Wien was flat. This established a calibration between the machine settings to achieve a straight orbit through the Wien at  $15^\circ$ . With this point calibrated, simulations for the other Wien angles required small changes in the design  $B \cdot dl$  value to match the Fopt data in line with the changes required in the operational machine. These  $B \cdot dl$  values were plotted against the respective Wien filter angles and fit with a linear function.

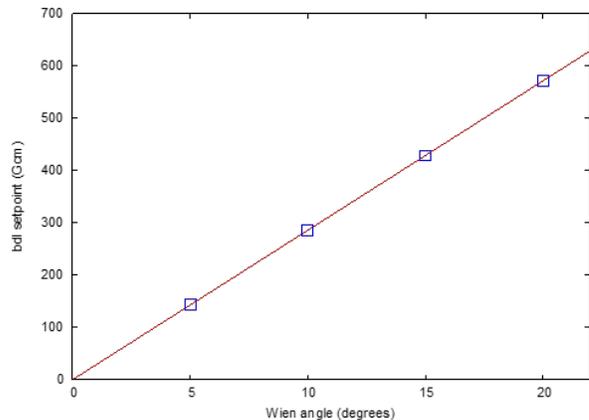


FIG. 8:  $B \cdot dl$  versus Wien filter angle fit to  $f(x) = 28.58x + .03$

	Wien $5^\circ$	Wien $10^\circ$	Wien $15^\circ$	Wien $20^\circ$
Design (Gcm)	136.07	282.33	428.59	574.85
Adjusted (Gcm)	147.17	293.93	436.99	579.55

The Wien filter was successfully integrated into the GPT CEBAF injector simulation. Figure 9 shows the simulation of a negative kick for corrector MBH1I04V (downstream of Wien filter), and Figure 10 shows the same corrector kick but with the addition of the Wien filter field map into the injector model. A small difference in the BPM measurement upstream of the Wien filter was observed, indicating either a small field leakage or a small difference between the Wien filter's calculated and actual magnetic field integral.

### IV. CONCLUSION

Due to the close agreement between simulation and experiment, the data suggest that the Wien filter model is

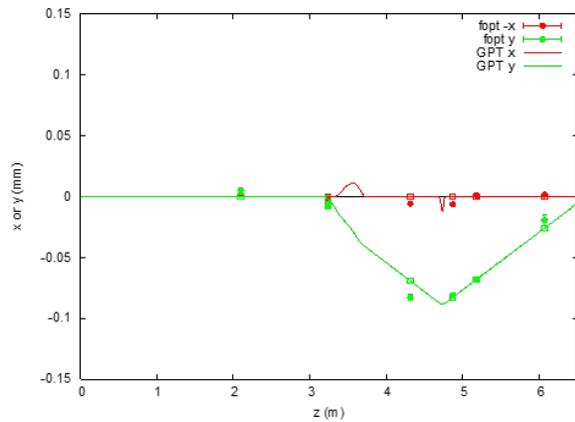


FIG. 9: corrector MBH1I04V kicked without Wien filter

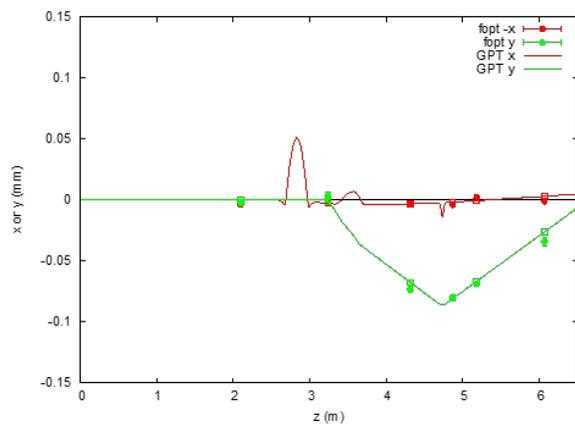


FIG. 10: corrector MBH1I04V kicked with addition of Wien filter

accurate. The addition of the Wien filter to the GPT injector model will serve to create more accurate simulations of the injector. The updated model will aid in future diagnostic tests of any beamline component downstream of the Wien filter, and allow users to easily calculate the electric and magnetic fields needed for the filter to function properly.

Results indicate discrepancies between the baseline model (without the Wien) and the machine for BPMs IPM1I04 and IPM0I02, as they consistently did not match simulation data. In the future, the response of these BPMs should be examined, and the models for neighboring elements on the beam line should be checked carefully to see if the model is incomplete or inaccurate in this region. There also seems to be a small effect upstream of the Wien filter when it is added, indicating upstream field leakage. However, this effect is very small and can be ignored.

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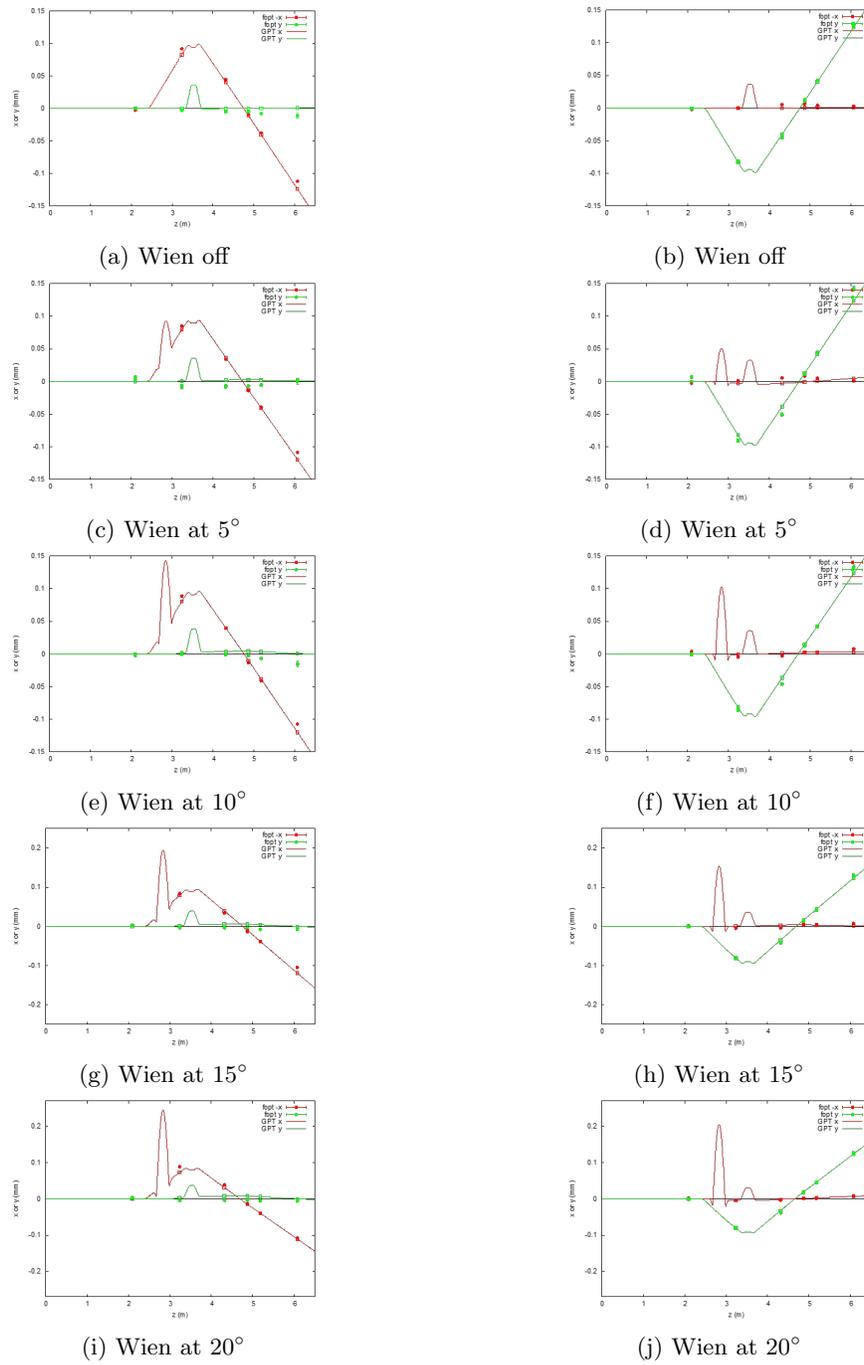


FIG. 11: MHB1I03H (left) and MHB1I03V (right) correctors with increasing Wien filter angle and negative corrector kicks

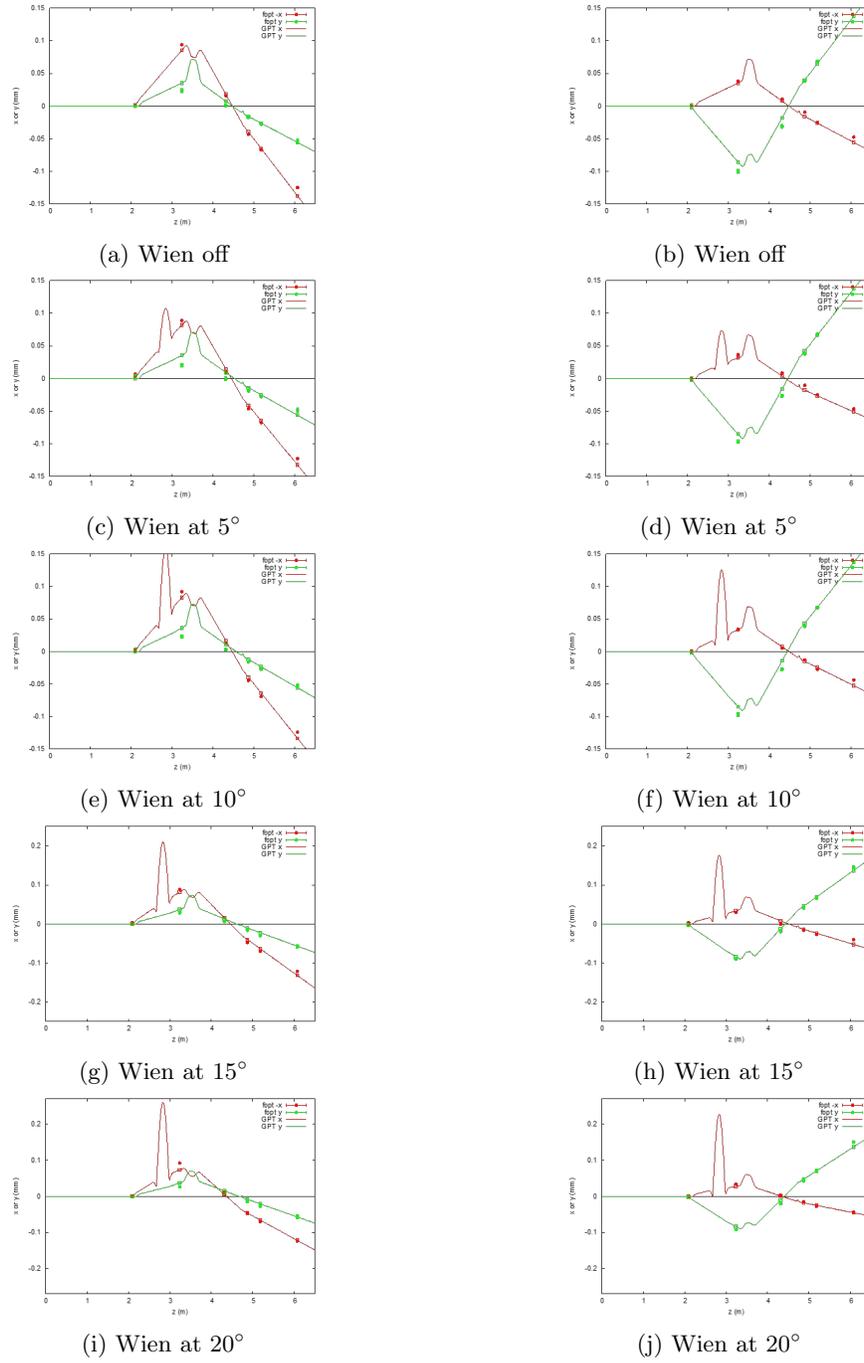


FIG. 12: MBH1I02H (left) and MBH1I02V (right) correctors with increasing Wien filter angle and negative corrector kicks

# Appendix A

## GPT Element Descriptions

There are four elements that can be used to model a Wien filter. Three (`wien`, `wienfindB`, and `wienfindE`) are simple, rather idealized models suitable for designing a Wien filter for a beamline, for example. These assume perfect field uniformity across the device and can include fringe fields for the magnetic field. They also provide varying flexibility to specify the field strengths. The fourth (`map3D_wien`) is a 3D field map based model. All four elements are composite elements based on existing GPT elements. The first three are based on `erect` and `rectmagnet`, and the field map version is based on `map3D_B` and `map3D_E`. This appendix provides the calling sequence for each Wien element. For details about the methods and field models used, the reader is directed to the GPT documentation.

### A.1 `wien`

Given the dimensions of the Wien filter and the field strengths, `wien` provides uniform fields with the specified strengths inside the Wien filter and can optionally calculate fringe fields for the magnetic field.

```
wien(ECS,a,b,L,E,B,d1,b1,b2  
    [,scope: LOCAL or GLOBAL])
```

**ECS** Element Coordinate System positioning information (see the coordinate system description in the GPT documentation)

**a** total length in x-direction [m]

**b** total length in y-direction [m]

**L** total length in z-direction [m]

**E** Electric field strength [V/m]

**B** Magnetic field strength [T]

**d1** Fringe field offset for entry and exit planes [m] (see `rectmagnet` in GPT documentation)

**b1** First coefficient of the fringe fields Enge function [ $\text{m}^{-1}$ ] (see `rectmagnet` in GPT documentation)

**b2** Second order coefficient of the fringe fields Enge function [ $\text{m}^{-2}$ ] (see `rectmagnet` in GPT documentation)

**scope** Optional argument to classify the element as local or global (see the coordinate system description in the GPT documentation). If omitted, the element is `GLOBAL`.

### A.2 `wienfindB` and `wienfindE`

`wienfindB` and `wienfindE` are similar to `wien` except that given one field strength they will calculate the missing compensating field strength based on the provided design  $\gamma$  for the beam.

#### A.2.1 `wienfindB`

Given the dimensions of the Wien filter, design  $\gamma$  for the beam, and the electric field strength, `wienfindB` calculates the compensating magnetic field [T] to provide uniform magnetic and electric fields inside the Wien filter. It can optionally calculate fringe fields for the compensating magnetic field.

```
wienfindB(ECS,a,b,L,E,G,d1,b1,b2  
    [,scope: LOCAL or GLOBAL])
```

**ECS** Element Coordinate System positioning information (see the coordinate system description in the GPT documentation)

**a** total length in x-direction [m]

**b** total length in y-direction [m]

**L** total length in z-direction [m]

**E** Electric field strength [V/m]

**G** design beam  $\gamma$  [unitless]

**d1** Fringe field offset for entry and exit planes [m] (see `rectmagnet` in GPT documentation)

- b1** First coefficient of the fringe fields Enge function [ $\text{m}^{-1}$ ] (see `rectmagnet` in GPT documentation)
- b2** Second order coefficient of the fringe fields Enge function [ $\text{m}^{-2}$ ] (see `rectmagnet` in GPT documentation)
- scope** Optional argument to classify the element as local or global (see the coordinate system description in the GPT documentation). If omitted, the element is `GLOBAL`.

### A.2.2 wienfindE

Given the dimensions of the Wien filter, design  $\gamma$  of the beam, and the magnetic field strength, `wienfindE` calculates the compensating electric field strength [ $\text{V/m}$ ] and provides uniform magnetic and electric fields in the Wien filter. It can optionally calculate fringe fields for the magnetic field.

`wienfindE(ECS,a,b,L,B,G,d1,b1,b2[,scope: LOCAL or GLOBAL])`

**ECS** Element Coordinate System positioning information (see the coordinate system description in the GPT documentation)

**a** total length in x-direction [m]

**b** total length in y-direction [m]

**L** total length in z-direction [m]

**B** Magnetic field strength [T]

**G** design beam  $\gamma$  [unitless]

**d1** Fringe field offset for entry and exit planes [m] (see `rectmagnet` in GPT documentation)

**b1** First coefficient of the fringe fields Enge function [ $\text{m}^{-1}$ ] (see `rectmagnet` in GPT documentation)

**b2** Second order coefficient of the fringe fields Enge function [ $\text{m}^{-2}$ ] (see `rectmagnet` in GPT documentation)

**scope** Optional argument to classify the element as local or global (see the coordinate system description in the GPT documentation). If omitted, the element is `GLOBAL`.

### A.3 map3D\_wien.c

`map3D_wien` reads 3D field maps for the magnetic and electric fields from the specified GDF files and scales the magnetic and electric field components with user provided constants, `Bfac` and `Efac`, respectively. For each active macroparticle's relative location in the Wien filter field maps, the element performs bilinear interpolation for each field map to determine the corresponding scaled

electric and magnetic field components.

`map3D_wien(ECS,Bfilename,Xb,Yb,Zb,Bx,By,Bz,Bfac,Efilename,Xe,Ye,Ze,Ex,Ey,Ez,Efac[,scope: LOCAL or GLOBAL])`

**ECS** Element Coordinate System positioning information (see the coordinate system description in the GPT documentation)

**Bfilename** Filename of GDF file containing the magnetic field components

**Xb** Name of the array in `Bfilename` with the x-coordinates [m] for the magnetic field components.

**Yb** Name of the array in `Bfilename` with the y-coordinates [m] for the magnetic field components.

**Zb** Name of the array in `Bfilename` with the z-coordinates [m] for the magnetic field components.

**Bx** Name of the array in `Bfilename` with the magnetic field in the x-direction

**By** Name of the array in `Bfilename` with the magnetic field in the y-direction

**Bz** Name of the array in `Bfilename` with the magnetic field in the z-direction

**Bfac** Multiplication factor for the magnetic field components (`Bfac*field component` results in field component in T)

**Efilename** Filename of GDF file containing the electric field components

**Xe** Name of the array in `Efilename` with the x-coordinates [m] for the electric field components.

**Ye** Name of the array in `Efilename` with the y-coordinates [m] for the electric field components.

**Ze** Name of the array in `Efilename` with the z-coordinates [m] for the electric field components.

**Ex** Name of the array in `Efilename` with the electric field in the x-direction

**Ey** Name of the array in `Efilename` with the electric field in the y-direction

**Ez** Name of the array in `Efilename` with the electric field in the z-direction

**Efac** Multiplication factor for the electric field components (`Efac*field component` results in field component in  $\text{V/m}$ )

**scope** Optional argument to classify the element as local or global (see the coordinate system description in the GPT documentation). If omitted, the element is `GLOBAL`.