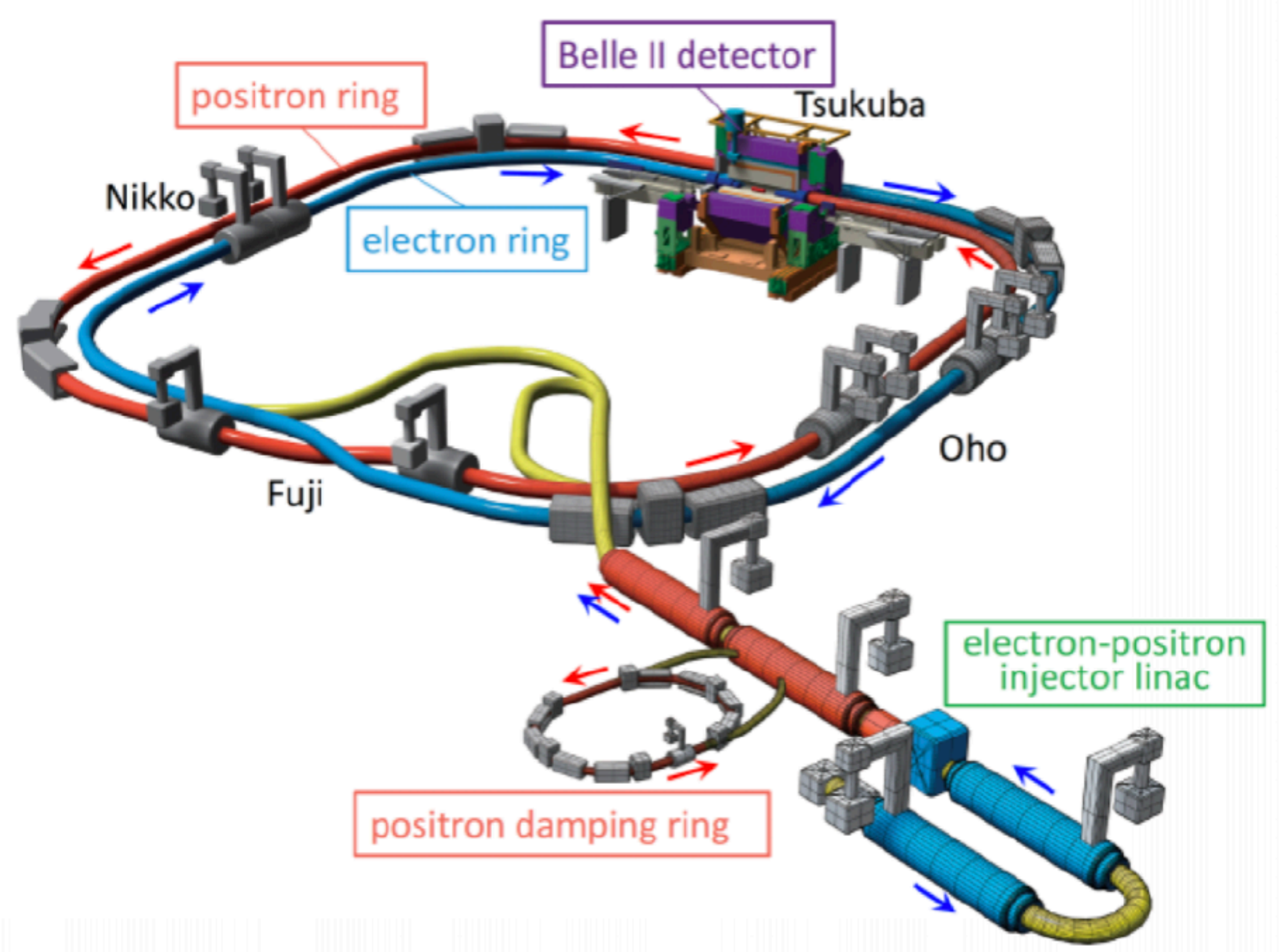
Spin Rotator Design for the SuperKEKB High Energy Ring in a Proposed Polarization Upgrade



Yuhao Peng

2021.09.24

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Purpose

$$A_{LR}^{f} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f \langle Pol \rangle \propto T_3^f - 2Q_f \sin^2\theta_W$$

Design a spin rotator for SuperKEKB High Energy Ring, to polarize the spin of the electron beam in the longitudinal direction at the interaction point (IP)

- Study of asymmetry between the identical processes with different electron beam handedness, which provides precision electroweak measurements; requires longitudinal polarization at the IP

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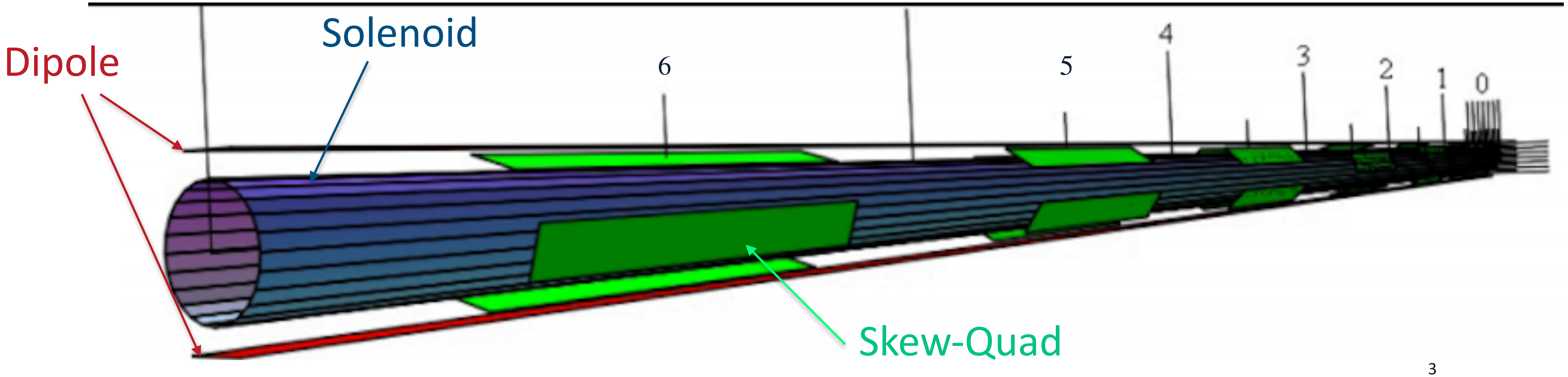
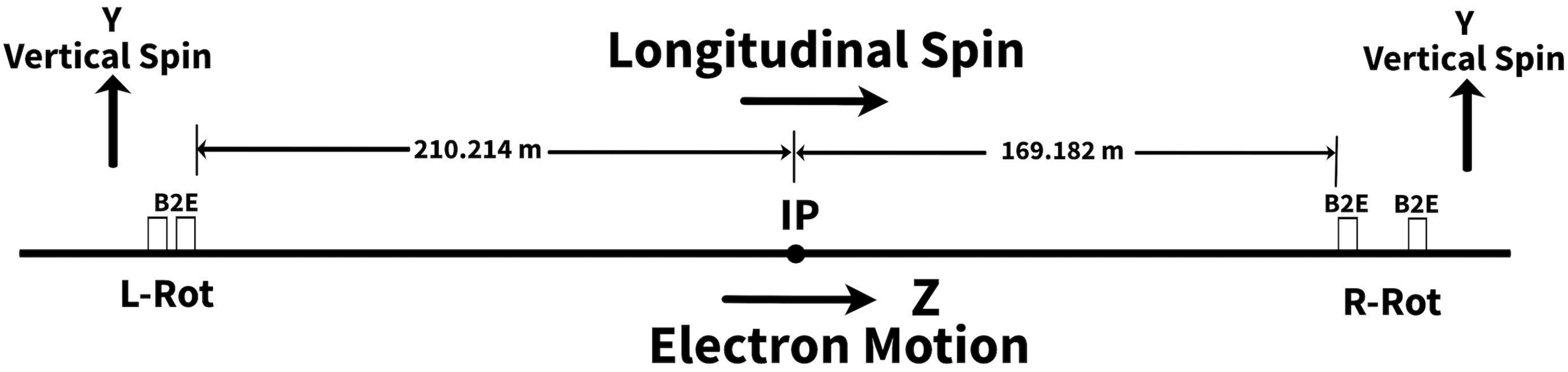
Rotator Magnet Structure

- Follows Uli Wienands's idea and direction:
- replace some existing ring dipoles(send) near the IP with the solenoid-dipole combined function magnets and maintain the original dipole strength
- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids



Spin Rotator



Right rotator(L-Rot) is to rotate the vertical spin to the longitudinal direction

Left rotator(R-Rot) is to rotate the longitudinal back to vertical

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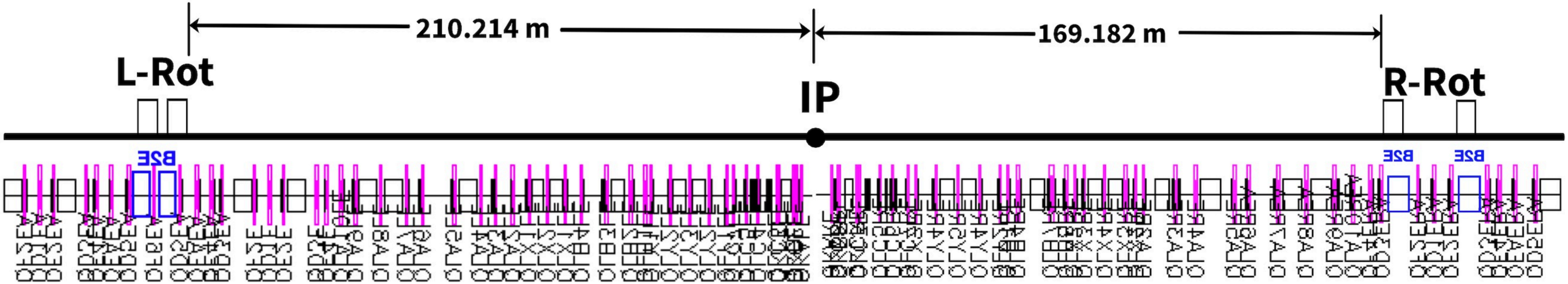

Overall spin rotation between the **L-Rot** and the IP:

~212.15˚ counterclockwise in the x-z plane

Overall spin rotation between the **IP** and the **R-Rot**:

~203.32˚ counterclockwise in the x-z plane

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Constraints of the Design

✤**Transparency**: Need to maintain the original **beam dynamics,** make the spin rotator transparent to the ring as much as possible

✤Physical constraints: All new magnets must be manufacturable and installable

- Solenoid strength can not exceed **5** T
- Skew-quad can not exceed **35** T/m

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Simulation Tool

- **Bmad** is an open-source software library (aka toolkit)created/maintained by David Sagan at Cornell University for simulating charged particles and X-rays. Étienne Forest's "Polymorphic Tracking Code" (**PTC**) is incorporated into it.

- **Tao** is a user-friendly interface to Bmad which gives general purpose simulation, based upon Bmad.

- **Bmad** via the **Tao** interface is a powerful and user-friendly tool used for viewing lattices, doing Twiss and orbit calculations, and performing nonlinear optimization on lattices

- Optimization Algorithm: **LMDIF** is to minimize the sum of the squares of nonlinear functions by a modification of the Levenberg-Marquardt algorithm

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Procedure of the Rot Design and Maintaining Transparency

- Model the Rotator Magnet with Bmad and do Sanity Check

- Design:
  - Find the appropriate dipoles to replace
  - Fit the strength of solenoids

- Transparency:
  - Decouple the x-y plane with skew quads
  - Rematch the optics by tuning ring quads near/in the rotator region
  - Fix the first order chromaticity by tunning ring sextupoles
  - Maintain Tune value Q (Noah Tessema will perform this step)

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Hkick Simulation

Rotator modelling requires a combination of dipole and solenoid-quadrupole

- Bmad has solenoid-quadrupole but does not have dipole-solenoid-quadrupole

- Following David Sagan's suggestion, use hkick(horizontal kick) to simulate the dipole(sbend)

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Patch Elements

Sbend is a curved element, but hkick is a straight element

- To simulate the curved element by a straight element, the hkick is sliced into small pieces and use patch elements(xoffset, xpitch, zoffest) to fix the floor coordinate (match the global geometry) at the exit of each slice

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Hkick Simulation

The hkick was initially sliced into 6 pieces to match the number of skew-quads and set the strength (bending angle) and the length to be same as the original B2E

- Fit the patch elements(xoffest, xpitch, zoffset) to fix the reference orbit(floor coord) at the exit of each piece

- Fit the hkick strength to fix the horizontal orbit(x, x')

- It requires at least two parameters to fix x and x', slightly varying the strength of 6 hkick pieces can fix the horizontal orbit at the exit of every 2nd hkick piece

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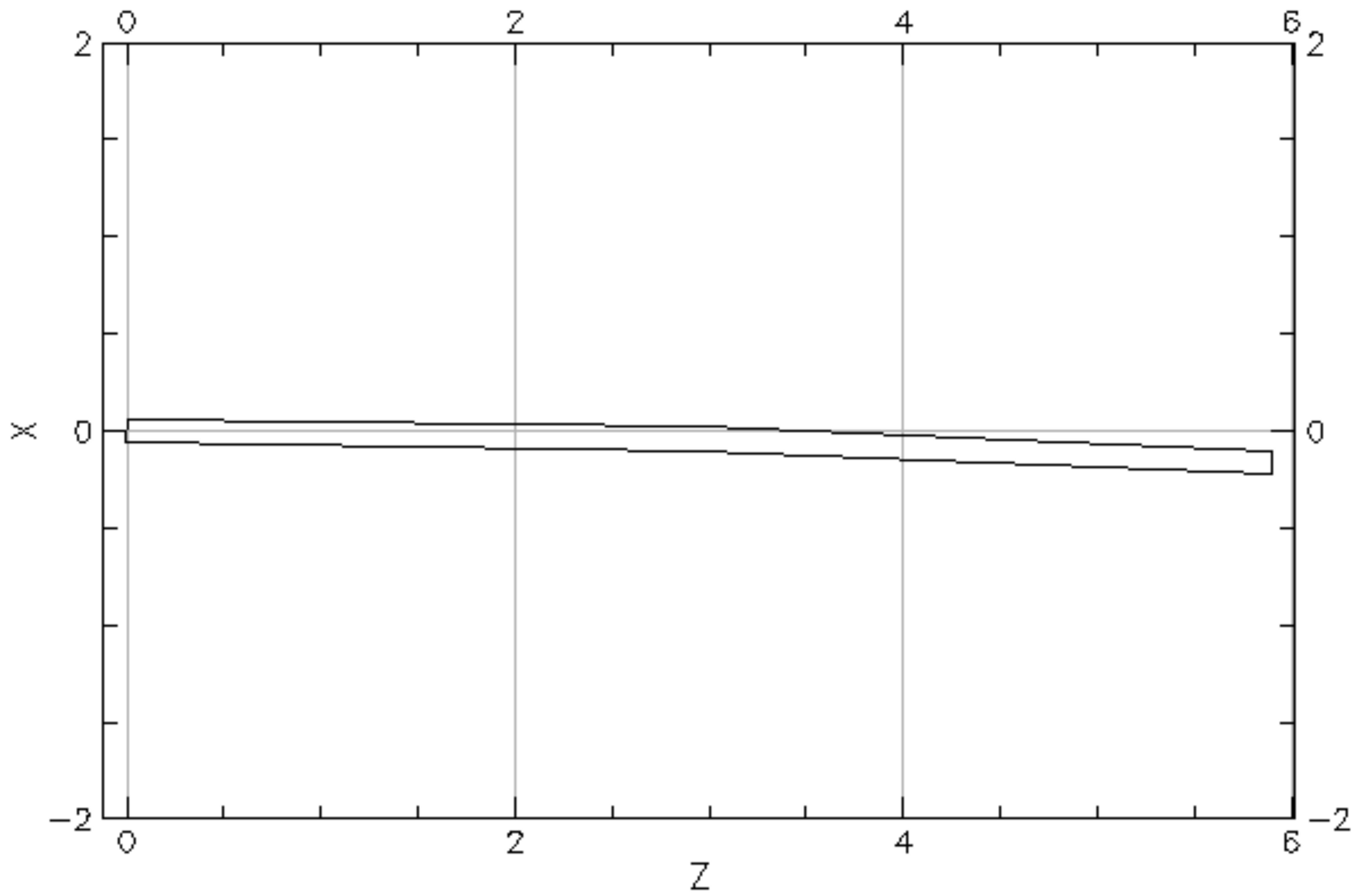
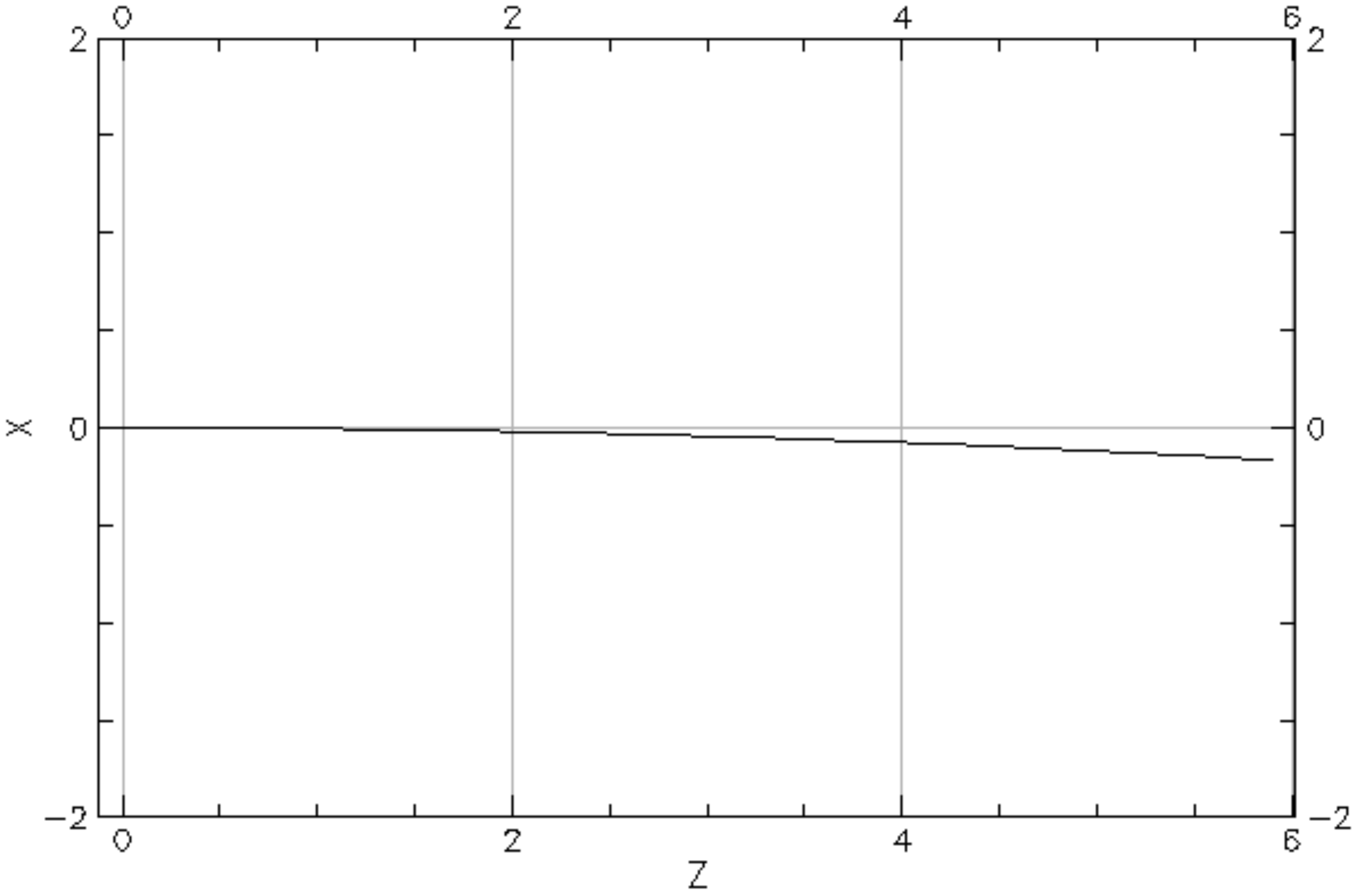
Comparison of floor coord between the B2E and the Hkick after fixing the floor coord and orbit



Original B2E



Hkick(6-piece sliced)

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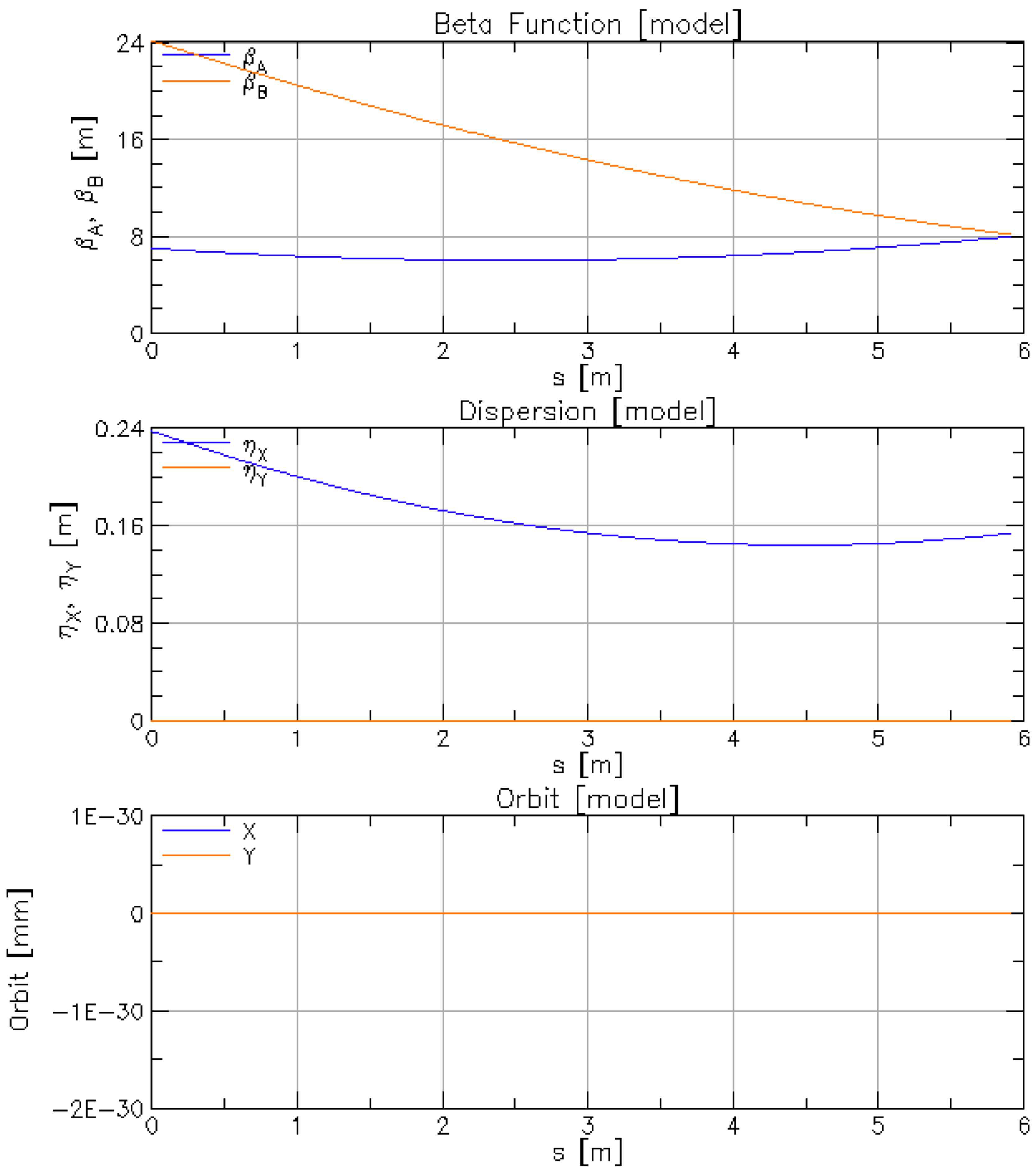
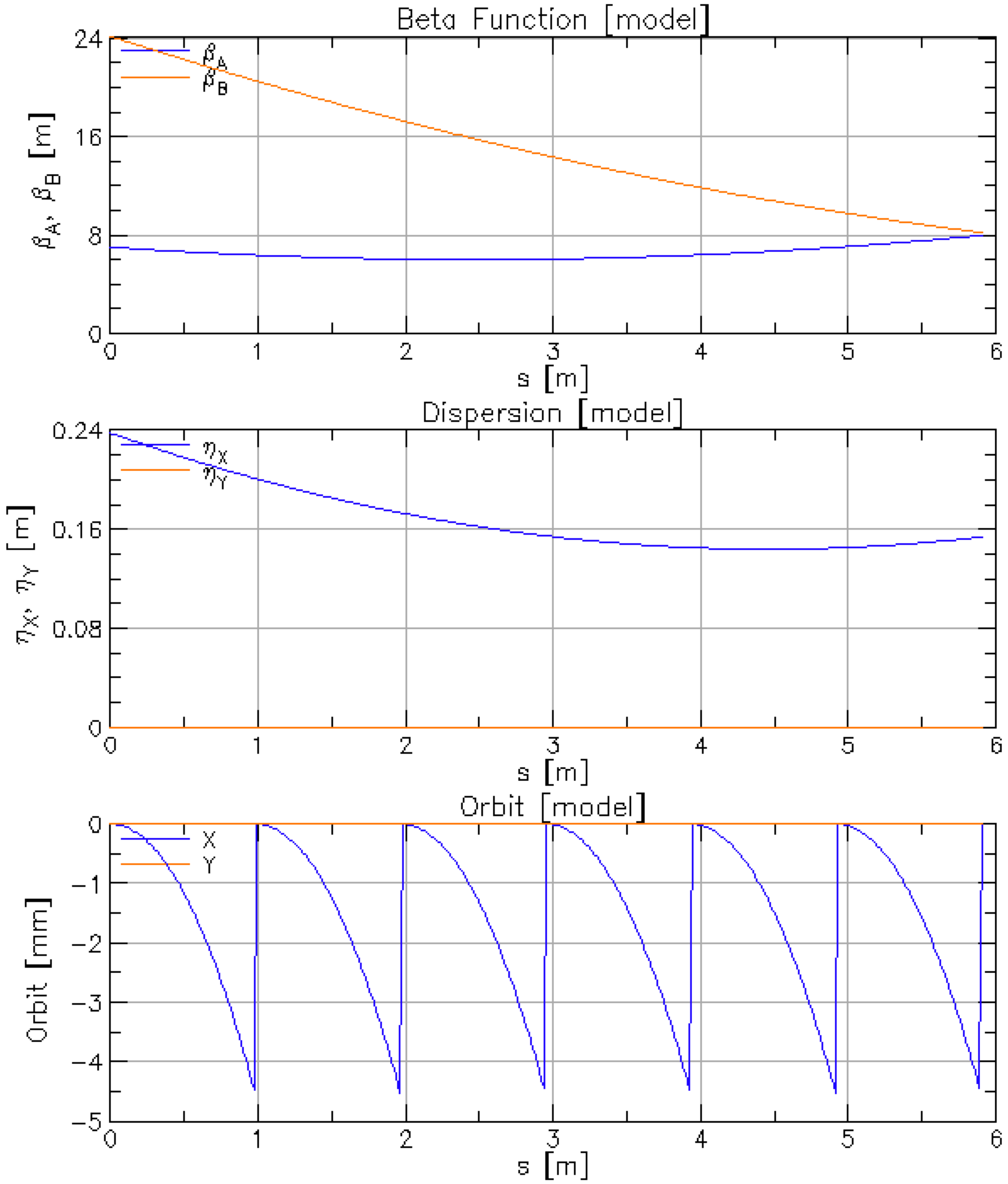
Comparison of orbit and Optical functions



Original B2E



Hkick(6 pieces)

Comparison of Spin

Original B2E

# Index	name	key	s	l	spin.x	spin.y	spin.z
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	1.0000000000
2	END	Marker	5.902	0.000	-0.7748218527	0.0000000000	0.6321796395

Hkick(6 pieces)

# Index	name	key	s	l	spin.x	spin.y	spin.z
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	1.0000000000
13	END	Marker	5.902	0.000	-0.7748218530	-0.0000000000	0.6321796391

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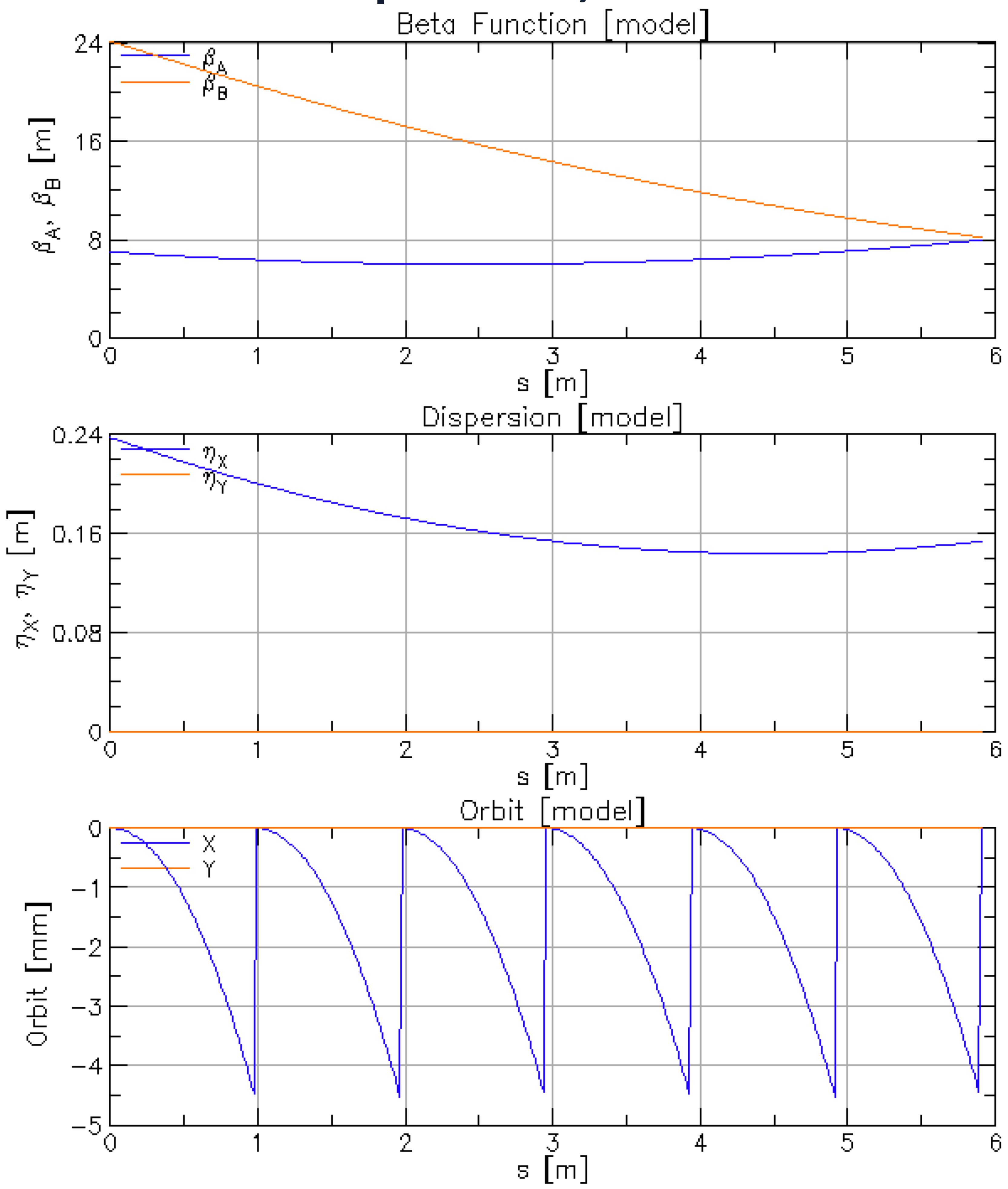
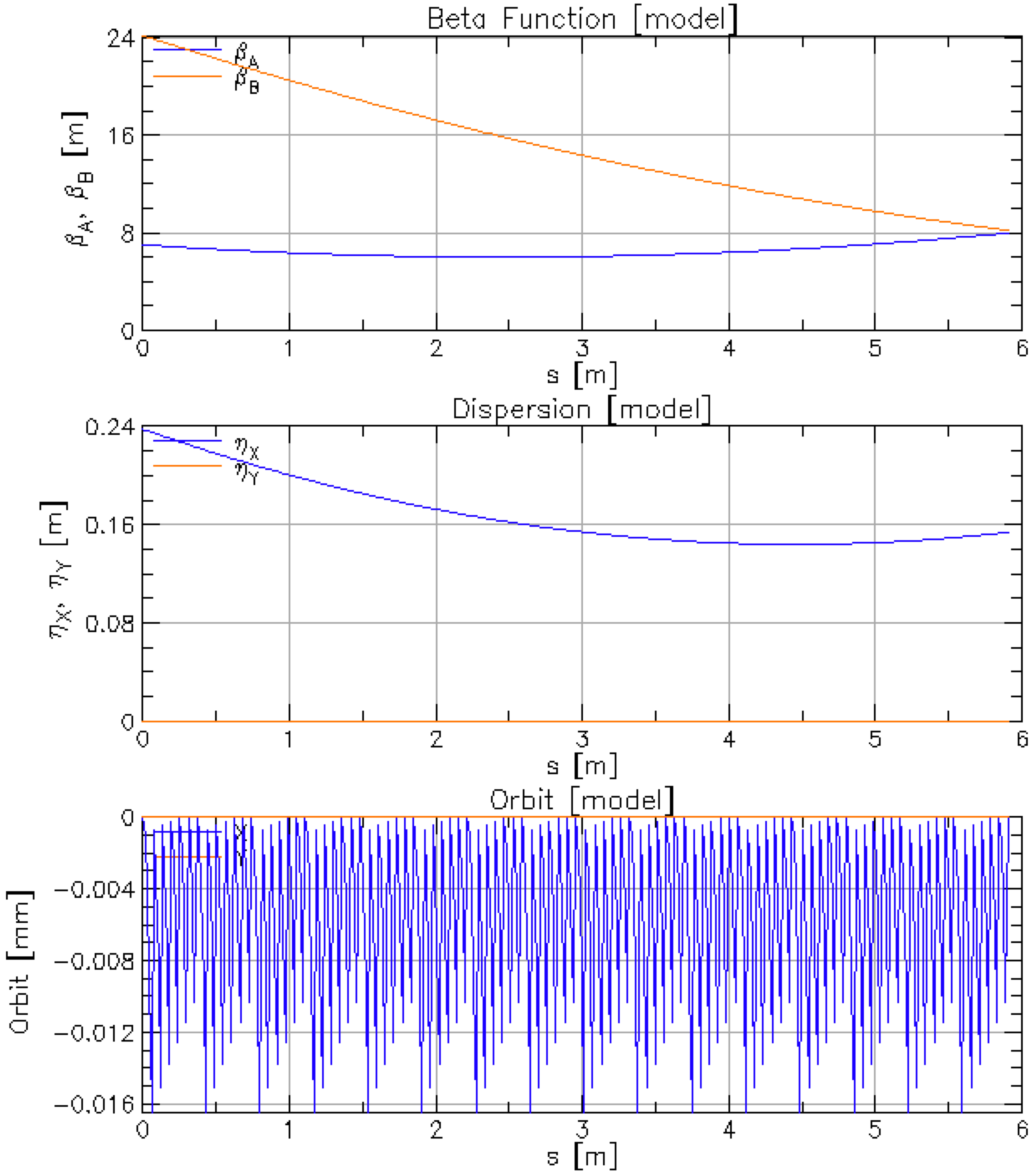
Slice Model

In order to reduce the non-physical orbit excursion, each piece of the hkick is further sliced into 16 pieces, 96 in total



Stand-alone Model(6-pieces)



Slice Model(96-pieces)

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Comparison of Spin

Original B2E

# Index	name	key	s	l	spin.x	spin.y	spin.z
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	1.0000000000
2	END	Marker	5.902	0.000	-0.7748218527	0.0000000000	0.6321796395

Hkick(96 sliced)

# Index	name	key	s	l	spin.x	spin.y	spin.z
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	1.0000000000
193	END	Marker	5.902	0.000	-0.7748218525	0.0000000000	0.6321796397

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Sanity Check

Replace 4 “B2E”(where the rotator magnets will be installed) with hkicks in the High Energy Ring

- Check if the floor coordinate is the same as the original (global geometry)

- Check if the orbit, optical functions, and ring parameters… are the same as the original

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Comparison of Floor Coord of Full Lattice

Original Ring

# Index	name	key	s	l	floor.x	floor.y	floor.z	floor.theta	floor.phi	floor.psi
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
6650	END	Marker	3016.315	0.000	0.0000000000	0.0000000000	-0.0000000055	-6.2831853072	0.0000000000	0.0000000000

Hkick Ring (From here if not mentioned, all the hkicks are 96 sliced)

# Index	name	key	s	l	floor.x	floor.y	floor.z	floor.theta	floor.phi	floor.psi
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
7414	END	Marker	3016.315	0.000	0.0000000000	0.0000000000	-0.0000000056	-6.2831853072	0.0000000000	0.0000000000

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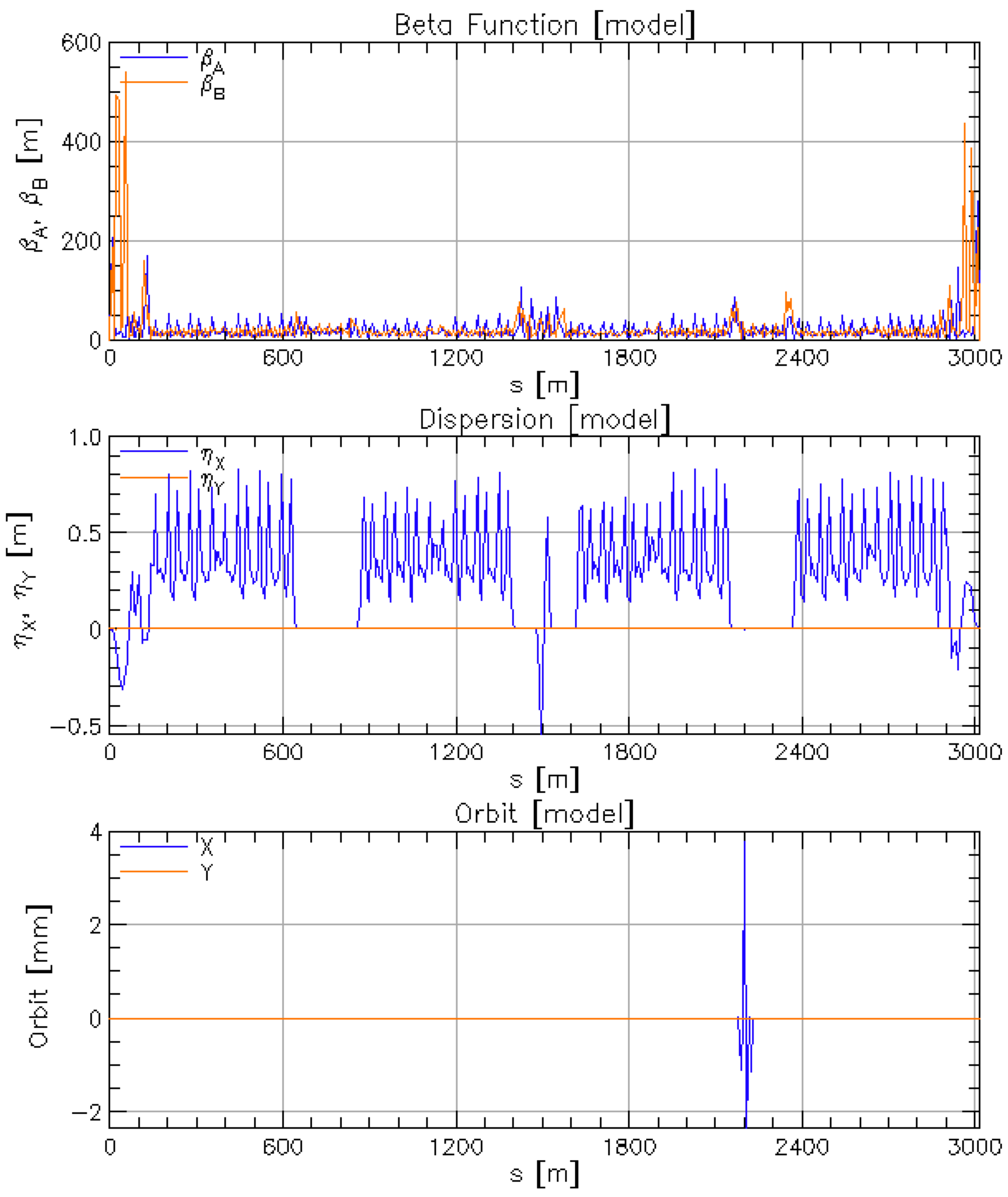
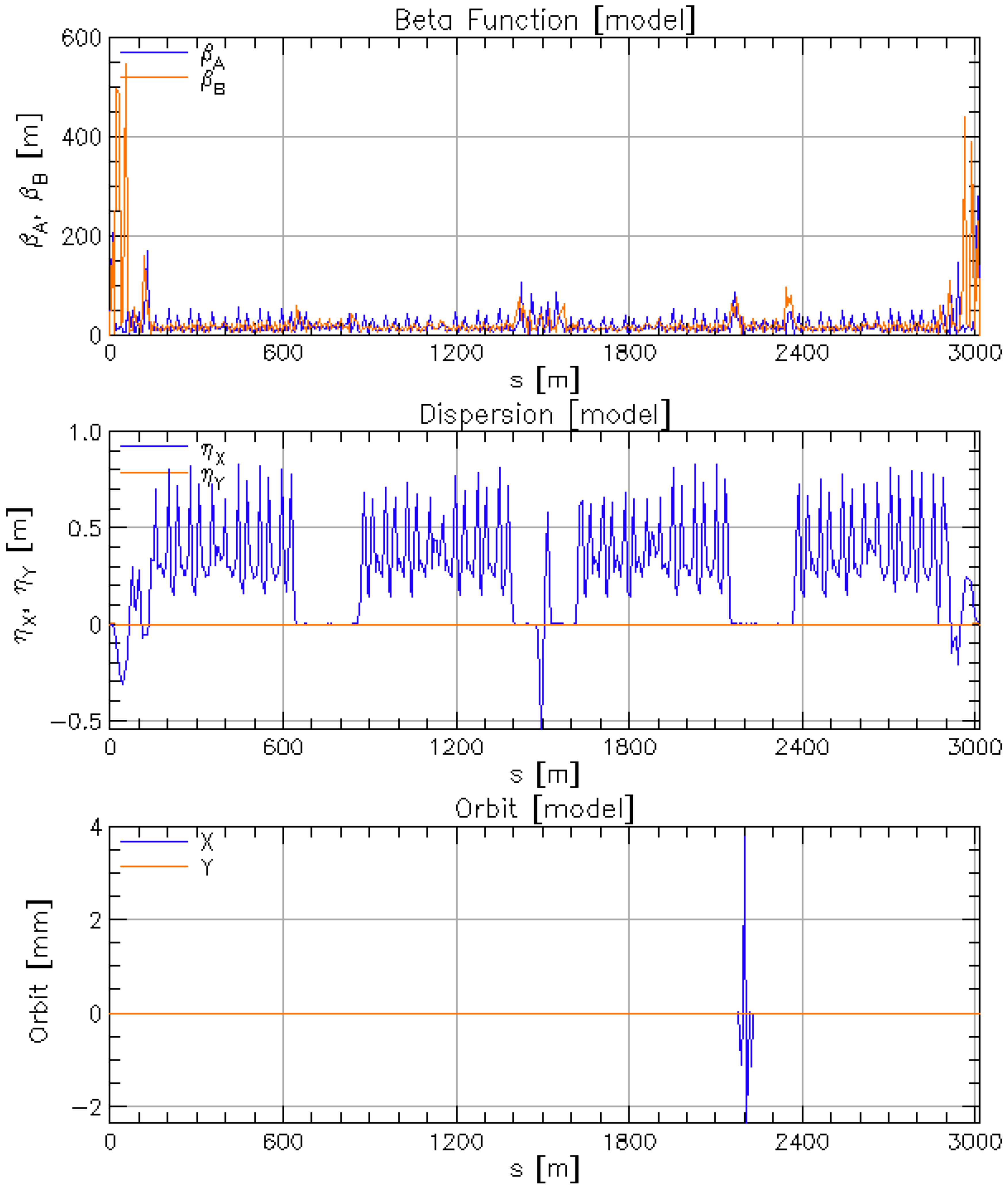
Comparison of the Orbit and Optical Functions of the Ring



Original



Hkick Ring

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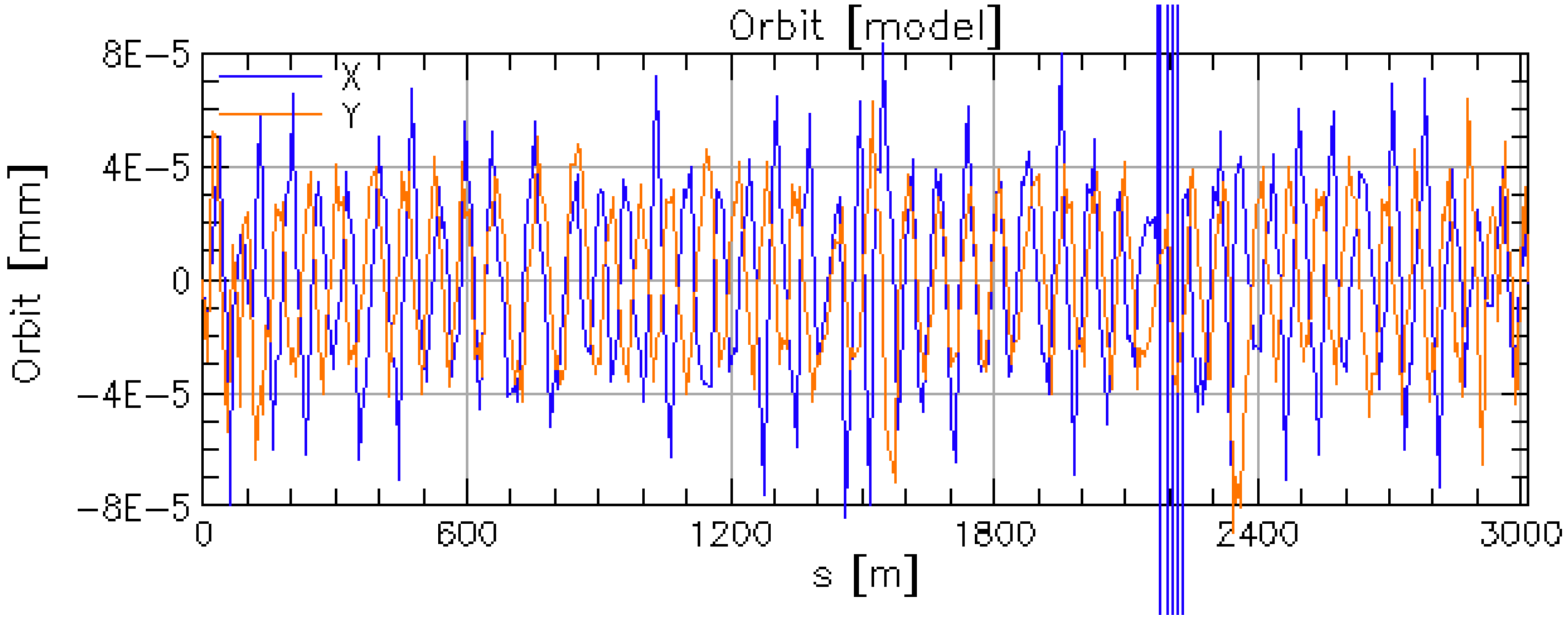
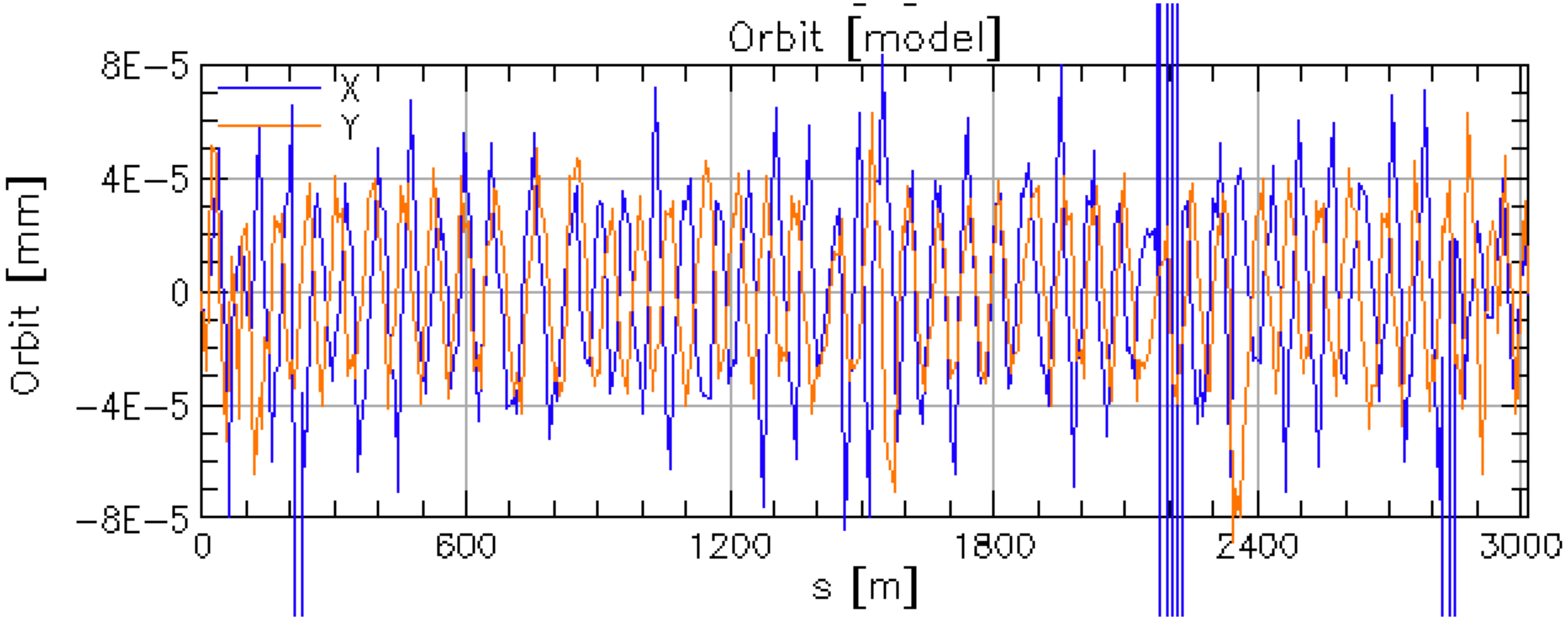
Comparison of Orbit of Full Lattice



Original



Hkick

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Comparison of Ring Parameters

Original

	X Model	X Design	Y Model	Y Design	
Q	45.530994	45.530994	43.580709	43.580709	! Tune
Chrom	1.593508	1.591895	1.622865	1.621568	! dQ/(dE/E)
J_damp	1.000064	0.999662	1.000002	1.000002	! Damping Partition #
Emittance	4.44061E-09	4.44277E-09	5.65367E-13	5.65331E-13	! Meters
Alpha_damp	1.78625E-04	1.78553E-04	1.78614E-04	1.78614E-04	! Damping per turn
Damping_time	5.63267E-02	5.63493E-02	5.63302E-02	5.63302E-02	! Sec

Hkick

	X Model	X Design	Y Model	Y Design	
Q	45.531143	45.531143	43.578638	43.578638	! Tune
Chrom	1.580251	1.577990	1.657455	1.655489	! dQ/(dE/E)
J_damp	0.999966	0.999398	1.000002	1.000002	! Damping Partition #
Emittance	4.44076E-09	4.44381E-09	5.69865E-13	5.69810E-13	! Meters
Alpha_damp	1.78607E-04	1.78505E-04	1.78613E-04	1.78613E-04	! Damping per turn
Damping_time	5.63324E-02	5.63644E-02	5.63304E-02	5.63304E-02	! Sec

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Fit the Solenoid-Quad

The particle will experience the solenoid-Quad field when it's turned on

The x-y plane is coupled due to the solenoid effect, so the horizontal motion will effect the vertical motion

Need to Refit the hkick to fix the horizontal orbit and introduce vkick to fix the vertical orbit when fitting the solenoid-Quad

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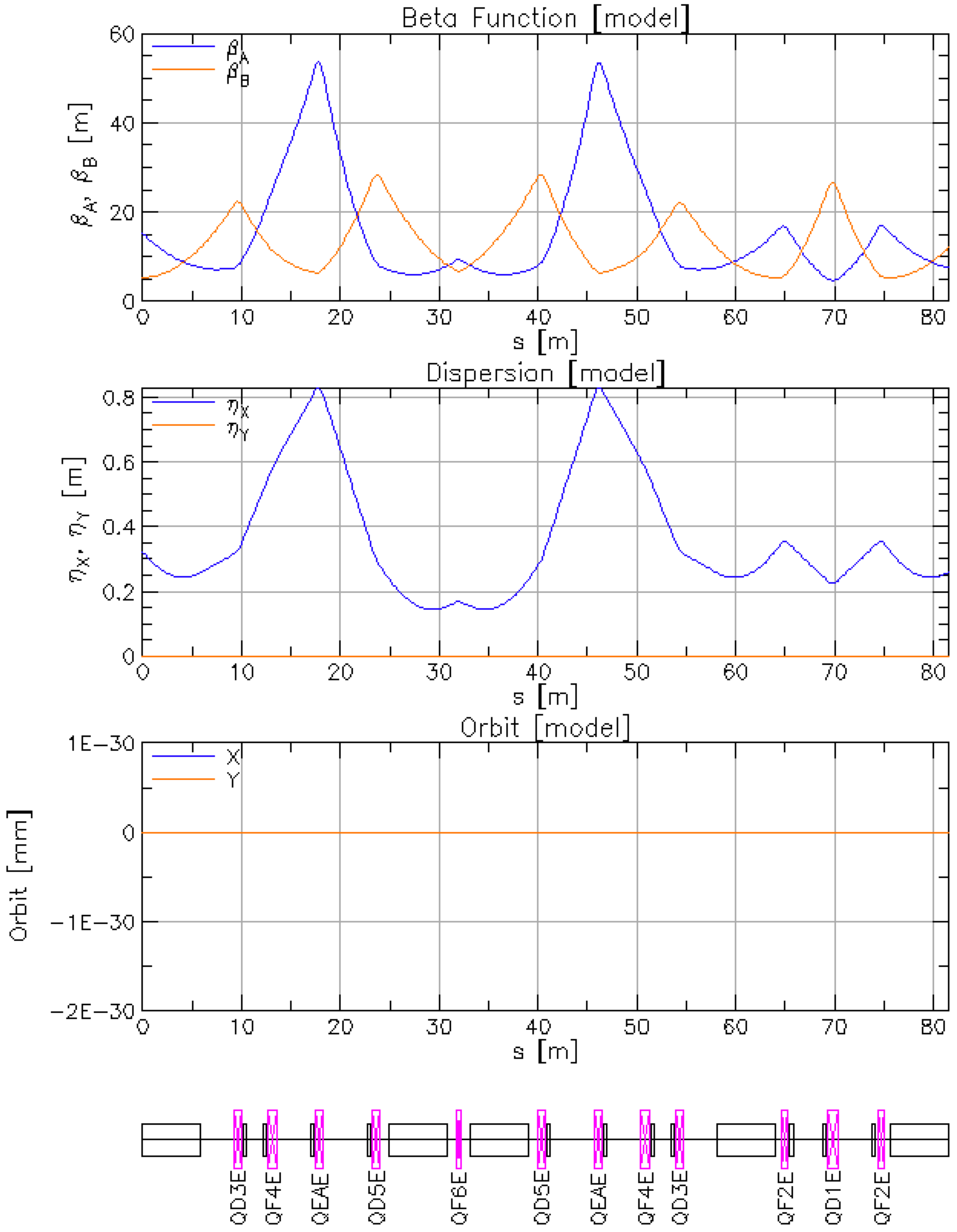
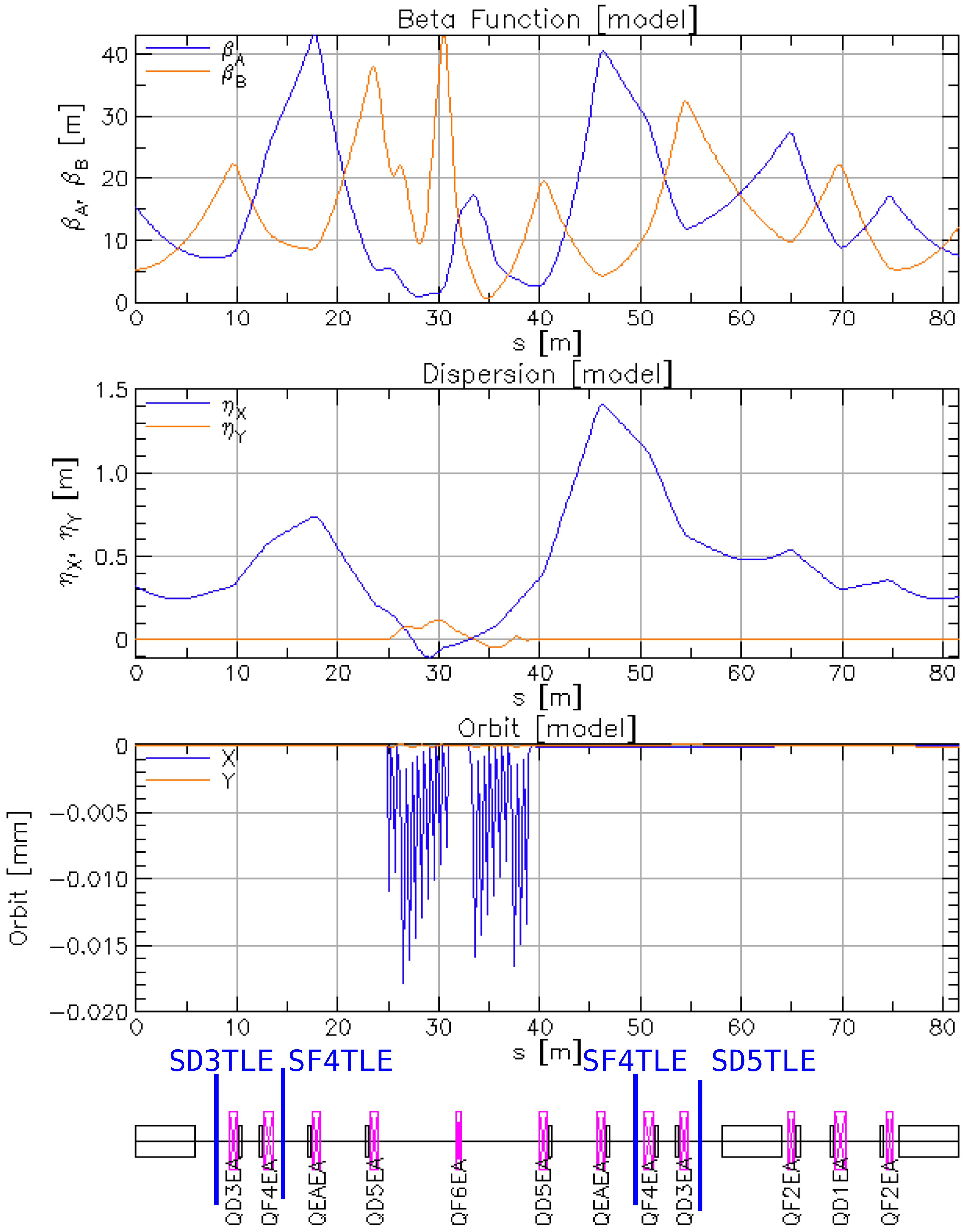
Comparison at L-Rot Region



Original



L-Rot

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L-Rot Solenoid Strength

Solenoid	Length (m)	Strength (T)
B2EALSQ	5.9	−4.843
B2EBLSQ	5.9	−2.577

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Skew-Quads in the L-Rot

Skew-Quads	Length (m)	Strength (T/m)	Tilt (rad)
B2EALSQ1	0.984	12.133	−0.426
B2EALSQ2	0.984	12.130	1.053
B2EALSQ3	0.984	−7.457	−0.988
B2EALSQ4	0.984	20.315	0.030
B2EALSQ5	0.984	16.350	−0.630
B2EALSQ6	0.984	19.340	1.383
B2EBLSQ1	0.984	13.266	0.651
B2EBLSQ2	0.984	−11.444	0.992
B2EBLSQ3	0.984	10.119	−1.494
B2EBLSQ4	0.984	8.024	−0.931
B2EBLSQ5	0.984	13.359	0.735
B2EBLSQ6	0.984	−4.404	0.868

Quads Comparison in the L-Rot Region

	Length	Original (k1L)	L-Rot (k1L)	Original (T/m)	L-Rot (T/m)
QD3E	0.82615	−0.175	−0.177	−4.948	−5.012
QF4E	1.01523	0.035	0.071	0.805	1.633
QEAE	0.82615	0.183	0.175	5.178	4.961
QD5E	0.82615	−0.179	−0.286	−5.074	−8.079
QF6E	0.55697	0.163	0.343	6.855	14.366
QF2E	0.55697	0.192	0.144	8.050	6.067
QD1E	1.01523	−0.255	−0.203	−5.867	−4.682

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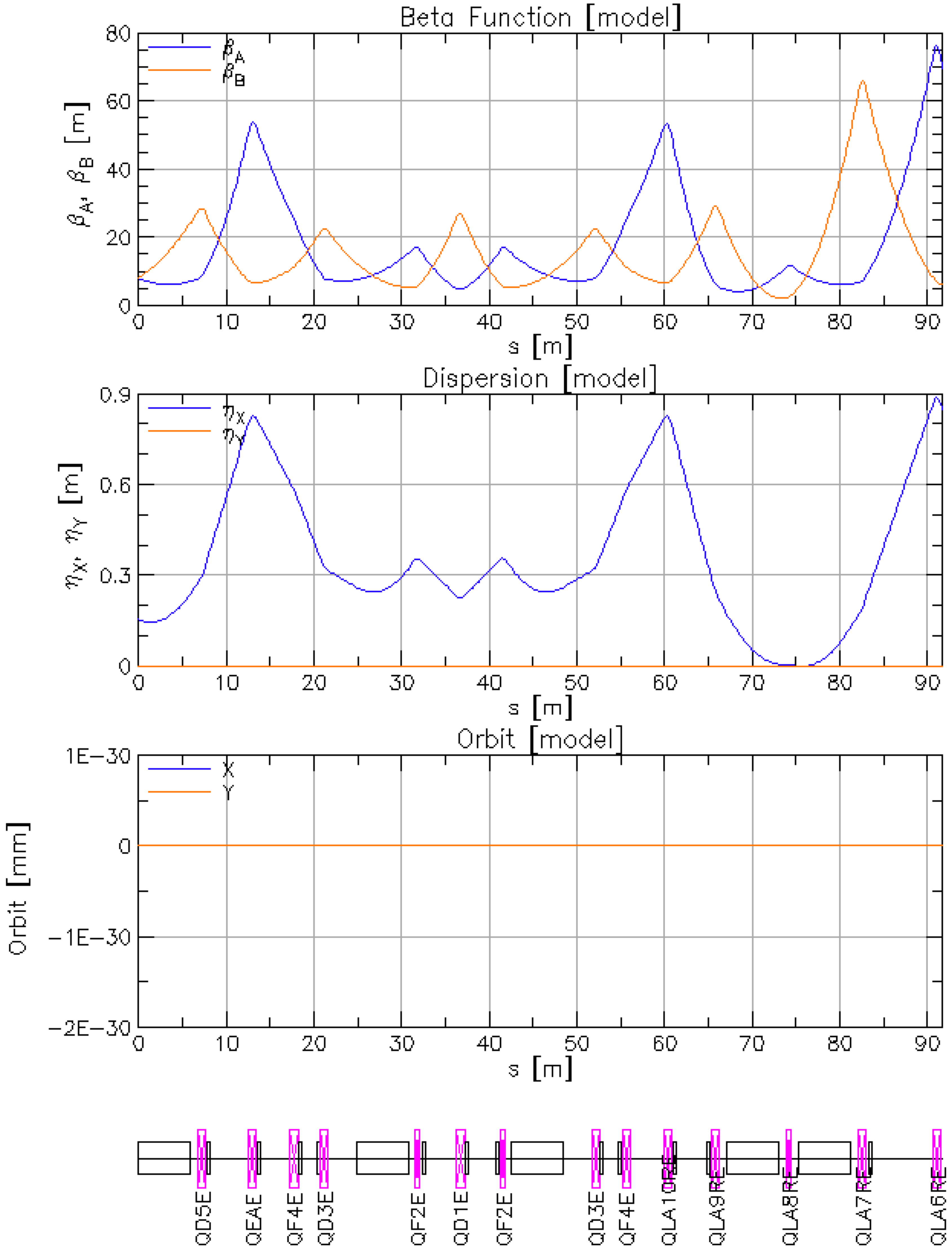
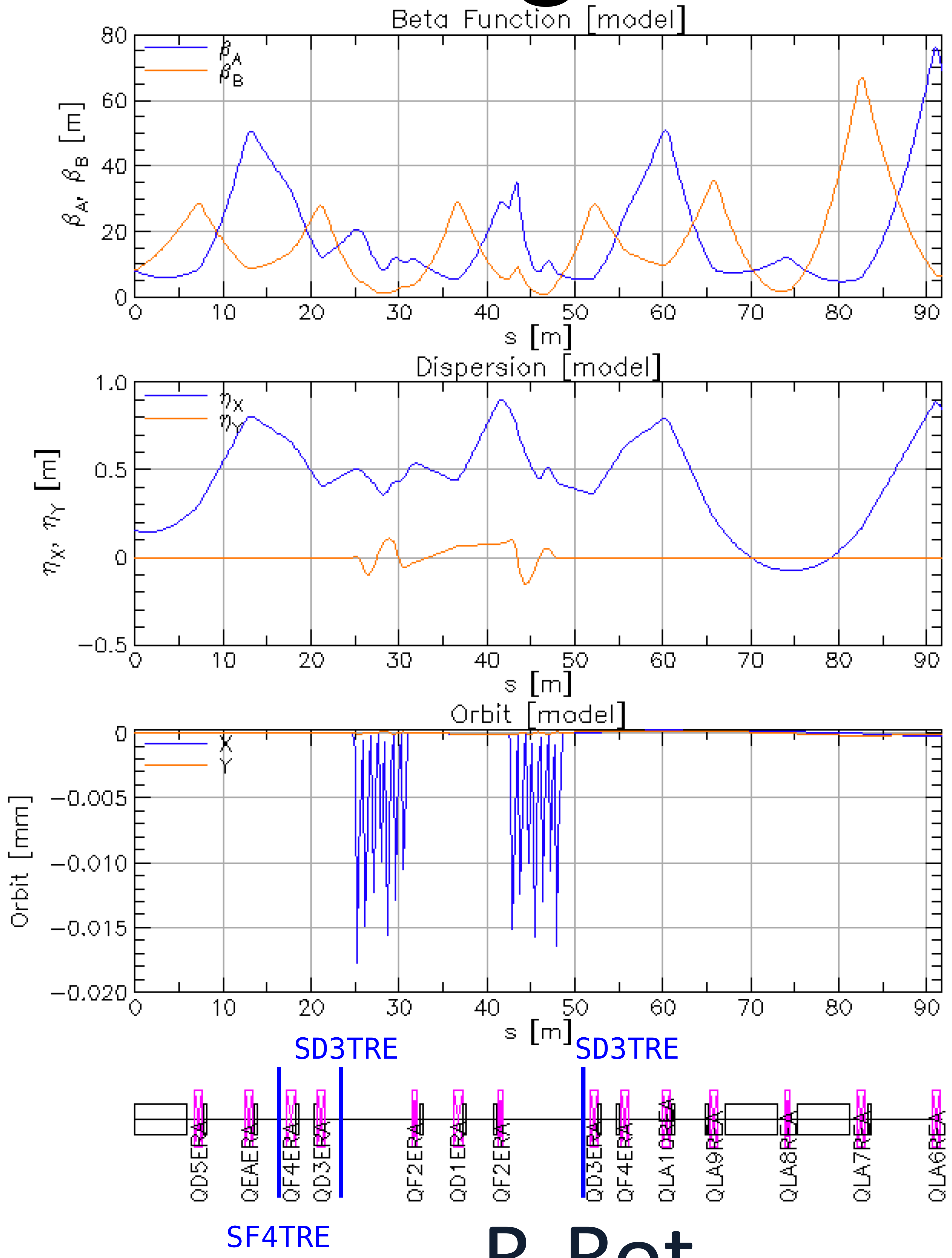
Comparison at R-Rot Region



Original



R-Rot

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R-Rot Solenoid Strength

Solenoid	Length (m)	Strength (T)
B2EARSQ	5.9	−3.608
B2EBRSQ	5.9	−3.942

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Skew-Quads in the R-Rot

Skew-Quads	Length (m)	Strength (T/m)	Tilt (rad)
B2EARSQ1	0.984	10.341	-2.610
B2EARSQ2	0.984	14.258	2.290
B2EARSQ3	0.984	1.032	2.327
B2EARSQ4	0.984	-13.451	-0.180
B2EARSQ5	0.984	14.258	-2.545
B2EARSQ6	0.984	-14.038	0.618
B2EBRSQ1	0.984	11.769	-2.480
B2EBRSQ2	0.984	12.648	2.238
B2EBRSQ3	0.984	6.663	-0.960
B2EBRSQ4	0.984	-13.429	-0.197
B2EBRSQ5	0.984	14.258	-2.846
B2EBRSQ6	0.984	-9.098	0.475

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Quads Comparison in the R-Rot Region

Quadrupole	Length (m)	Original k1L	R-Rot k1L	Original (T/m)	R-Rot (T/m)
QD5E	0.82615	−0.179	−0.165	−5.074	−4.667
QEAE	0.82615	0.183	0.154	5.178	4.362
QF4E	1.01523	0.035	0.067	0.805	1.538
QD3E	0.82615	−0.175	−0.251	−4.948	−7.088
QF2E	0.55697	0.192	0.183	8.050	7.659
QD1E	1.01523	−0.255	−0.274	−5.867	−6.311
QLA10RE	0.82615	0.202	0.185	5.718	5.234
QLA9RE	0.82615	−0.237	−0.226	−6.703	−6.385
QLA8RE	0.55697	0.203	0.169	8.527	7.106
QLA7RE	0.82615	−0.192	−0.195	−5.438	−5.522
QLA6RE	0.82615	0.202	0.205	5.716	5.808

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Linear Relationship Between the Chromaticity and the Sextupole Strength

$$
\begin{cases}
\xi_x = \sum_i m_i x_i + x_0 \\
\xi_y = \sum_i n_i x_i + y_0
\end{cases}
$$

- Where ξ_x, ξ_y is the first order chromaticity
- x_i is the strength of sextupole
- m_i, n_i only depends on local optics
- x_0, y_0 is the chromaticity when all tuning sextupoles are turned off

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Sextupoles used for fixing the first order chromaticity

SD5TLE, SF4TLE, and SD3TRE pairs are turned off because the phase difference between these pairs is no longer π

	length (m)	B2(Original)	B2(Rot)	K2L(Original)	K2L(Rot)
SD3TLE	1.03	-3.577	-4.027	-7.153	-8.054
SF6TLE	0.334	0.818	1.008	1.635	2.015
SD7TLE	1.03	-3.607	-4.062	-7.214	-8.123
SD7TRE	1.03	-1.730	-4.042	-3.459	-8.084
SF6TRE	0.334	0.829	1.596	1.659	3.192
SD5TRE	1.03	-1.695	-4.088	-3.390	-8.177

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Check the global geometry with Rot Installed in the Ring

Original

# Index	name	key	s	l	floor.x	floor.y	floor.z	floor.theta	floor.phi	floor.psi
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
6650	END	Marker	3016.315	0.000	0.0000000000	0.0000000000	-0.0000000055	-6.2831853072	0.0000000000	0.0000000000

Rot

# Index	name	key	s	l	floor.x	floor.y	floor.z	floor.theta	floor.phi	floor.psi
0	BEGINNING	Beginning_Ele	0.000	---	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
7414	END	Marker	3016.315	0.000	0.0000000000	0.0000000000	-0.0000000056	-6.2831853072	0.0000000000	0.0000000000

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Longitudinal spin alignment at the IP

- The spin track result shows a longitudinal spin alignment >99.99% with the rotator installed in the High Energy Ring

Spin Component	Entrance of Rot	IP	Exit
X	−0.0000032792024300	−0.0000044677361868	−0.0000063748934711
Y	0.9999999999802550	0.0000026796195603	0.9999999999793680
Z	−0.0000053600276775	0.9999999999864290	0.0000007825194459

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IP Status

Original

```
Twiss at end of element:
                          A             B       |      Cbar                          C_mat
  Beta (m)           0.05998852    0.00099672   |  0.00001394   0.00005392      0.00010814   0.00000042
  Alpha              0.00000597    0.00006932   | -0.00000058   0.00000283     -0.00007474   0.00000036
  Gamma (1/m)       16.66985613 1003.28929671   |  Gamma_c =    1.00000000      Mode_Flip = F
  Phi (rad)          0.00000000    0.00000000             X               Y               Z
  Eta (m)            0.00000001    0.00000000      0.00000001      0.00000000      0.00000000
  Etap              -0.00000037   -0.00000060     -0.00000037     -0.00000060      1.00000000
  Sigma              0.00001638    0.00000021      0.00001638      0.00000021

Orbit:  Positron   State: Alive
          Position[mm] Momentum[mrad]        Spin    |
  X:       -0.00000137    -0.00000539   0.00333570   | t_particle [sec]:        0.00000000E+00  E_tot: 7.00729E+09
  Y:       -0.00000051    -0.00007224   0.99996491   | t_part-t_ref [sec]:      0.00000000E+00  PC:    7.00729E+09
  Z:        0.00000000     0.00000000   0.00768449   | (t_ref-t_part)*Vel [m]:  0.00000000E+00  Beta:  0.999999997
```

Rot

```
Twiss at end of element:
                          A             B       |      Cbar                          C_mat
  Beta (m)           0.06000001    0.00100333   |  0.00000049   0.00005373      0.00000530   0.00000042
  Alpha              0.00003353    0.00354778   | -0.00000020  -0.00000019     -0.00002612  -0.00000002
  Gamma (1/m)       16.66666296  996.69118486   |  Gamma_c =    1.00000000      Mode_Flip = F
  Phi (rad)          0.00000000    0.00000000             X               Y               Z
  Eta (m)           -0.00000009    0.00000010     -0.00000009      0.00000010      0.00000000
  Etap              -0.00000750   -0.00000504     -0.00000750     -0.00000504      1.00000000
  Sigma              0.00001638    0.00000021      0.00001638      0.00000021

Orbit:  Positron   State: Alive
          Position[mm] Momentum[mrad]        Spin    |
  X:       -0.00000130    -0.00005444  -0.00000447   | t_particle [sec]:        0.00000000E+00  E_tot: 7.00729E+09
  Y:       -0.00000051     0.00004703   0.00000268   | t_part-t_ref [sec]:      0.00000000E+00  PC:    7.00729E+09
  Z:        0.00000000     0.00000000   1.00000000   | (t_ref-t_part)*Vel [m]:  0.00000000E+00  Beta:  0.999999997
```

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Comparison of Ring Parameters With First Order Chormaticity Fixed

Original

	X Model	X Design	Y Model	Y Design	
Q	45.530994	45.530994	43.580709	43.580709	! Tune
Chrom	1.593508	1.591895	1.622865	1.621568	! dQ/(dE/E)
J_damp	1.000064	0.999662	1.000002	1.000002	! Damping Partition #
Emittance	4.44061E-09	4.44277E-09	5.65367E-13	5.65331E-13	! Meters
Alpha_damp	1.78625E-04	1.78553E-04	1.78614E-04	1.78614E-04	! Damping per turn
Damping_time	5.63267E-02	5.63493E-02	5.63302E-02	5.63302E-02	! Sec

Rot

	X Model	X Design	Y Model	Y Design	
Q	45.777566	45.777566	44.446774	44.446774	! Tune
Chrom	1.593508	1.541611	1.622865	1.700876	! dQ/(dE/E)
J_damp	0.984214	0.983584	1.005265	1.005263	! Damping Partition #
Emittance	4.88965E-09	4.89356E-09	4.01654E-12	4.01059E-12	! Meters
Alpha_damp	1.75793E-04	1.75681E-04	1.79553E-04	1.79553E-04	! Damping per turn
Damping_time	5.72340E-02	5.72706E-02	5.60354E-02	5.60355E-02	! Sec

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Future Steps

An Alternative Solution has been found, need to confirm which one is to be used

Long Term Tracking (2M turns required)

Fix the Tune value

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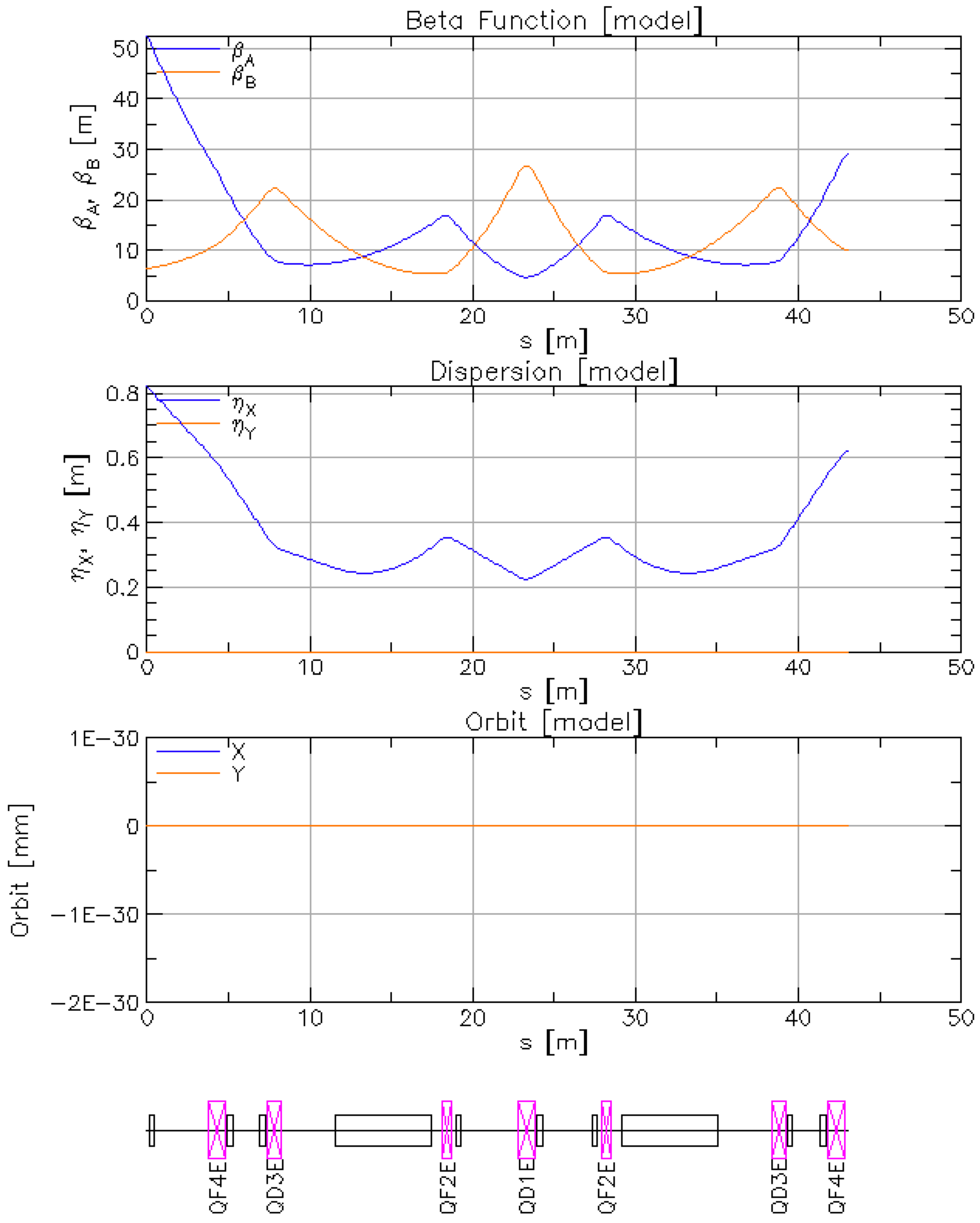
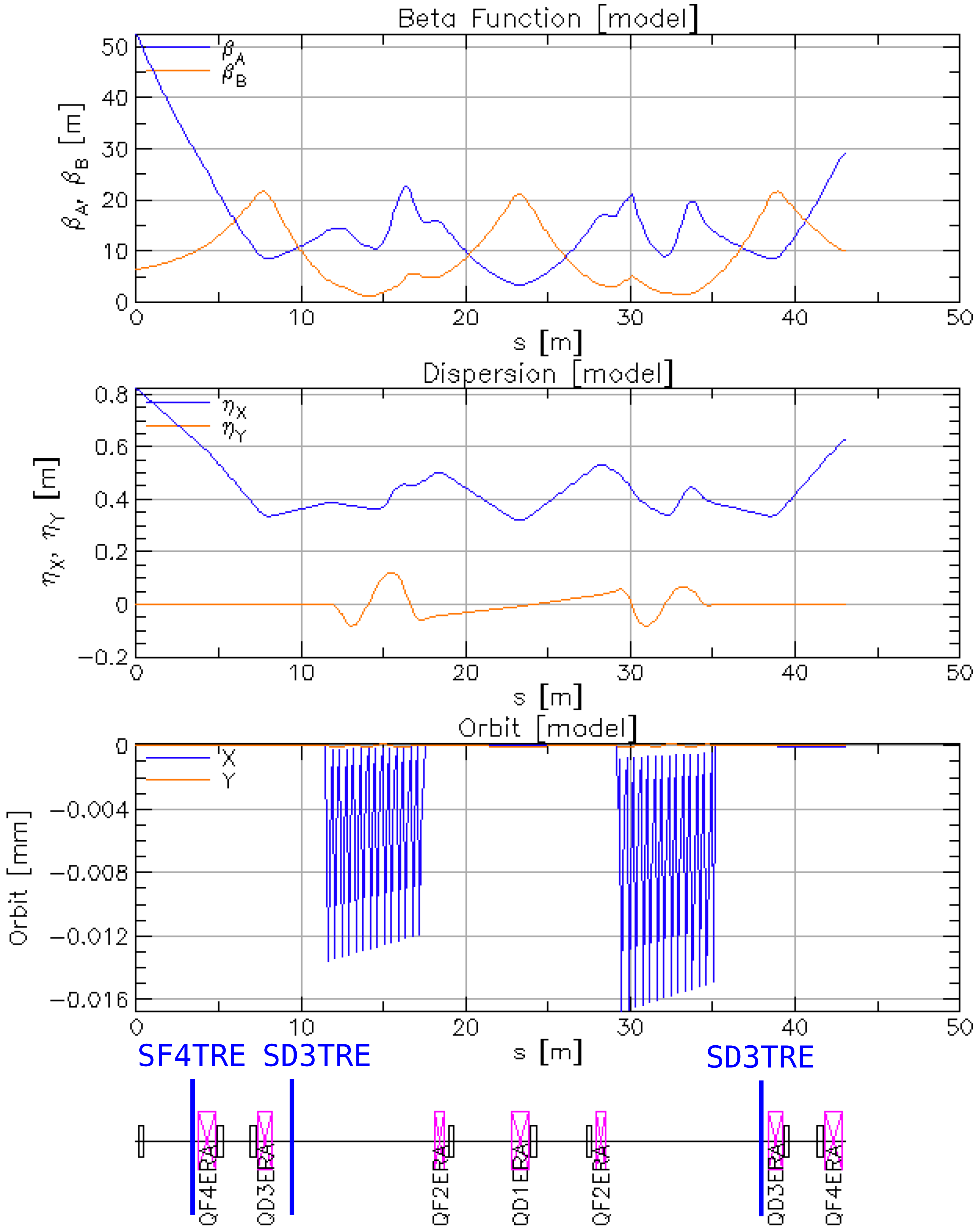
Alternative R-Rot



Original



R-Rot

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Alternative Ring Quads

Quadrupole	Length (m)	Original k1L	R-Rot k1L	Original (T/m)	R-Rot (T/m)
QF4E	1.01523	0.035	0.031	0.805	0.716
QD3E	0.82615	−0.175	−0.256	−4.948	−7.230
QF2E	0.55697	0.192	0.161	8.050	6.766
QD1E	1.01523	−0.255	−0.273	−5.867	−6.285

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Alternative Sextupoles

	length (m)	B2(Original)	B2(Rot)	K2L(Original)	K2L(Rot)
SD3TLE	1.03	-3.577	-4.065	-7.153	-8.131
SF6TLE	0.334	0.818	1.080	1.635	2.160
SD7TLE	1.03	-3.607	-3.854	-7.214	-7.707
SD7TRE	1.03	-1.730	-4.150	-3.459	-8.300
SD5TRE	1.03	-1.695	-4.005	-3.390	-8.010
SF4TRE	0.334	0.505	1.274	1.010	2.547

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IP Status

Original

```
Twiss at end of element:
                        A             B         |      Cbar                        C_mat
 Beta (m)          0.05998852    0.00099672    |  0.00001394   0.00005392     0.00010814   0.00000042
 Alpha             0.00000597    0.00006932    | -0.00000058   0.00000283    -0.00007474   0.00000036
 Gamma (1/m)      16.66985613 1003.28929671    |  Gamma_c =    1.00000000     Mode_Flip = F
 Phi (rad)         0.00000000    0.00000000           X             Y             Z
 Eta (m)           0.00000001    0.00000000     0.00000001    0.00000000    0.00000000
 Etap             -0.00000037   -0.00000060    -0.00000037   -0.00000060    1.00000000
 Sigma             0.00001638    0.00000021     0.00001638    0.00000021

Orbit:   Positron   State: Alive
         Position[mm] Momentum[mrad]      Spin    |
 X:       -0.00000137   -0.00000539  0.00333570  | t_particle [sec]:        0.00000000E+00  E_tot: 7.00729E+09
 Y:       -0.00000051   -0.00007224  0.99996491  | t_part-t_ref [sec]:      0.00000000E+00  PC:    7.00729E+09
 Z:        0.00000000    0.00000000  0.00768449  | (t_ref-t_part)*Vel [m]:  0.00000000E+00  Beta:  0.999999997
```

Alternative Rot

```
Twiss at end of element:
                        A             B         |      Cbar                        C_mat
 Beta (m)          0.06000125    0.00099437    | -0.00000039   0.00005383    -0.00000349   0.00000042
 Alpha             0.00003854   -0.00118179    |  0.00000001  -0.00000285     0.00000127  -0.00000037
 Gamma (1/m)      16.66632041 1005.66350157    |  Gamma_c =    1.00000000     Mode_Flip = F
 Phi (rad)         0.00000000    0.00000000           X             Y             Z
 Eta (m)          -0.00000079    0.00000009    -0.00000079    0.00000009    0.00000000
 Etap             -0.00000433   -0.00003241    -0.00000433   -0.00003241    1.00000000
 Sigma             0.00001638    0.00000021     0.00001638    0.00000021

Orbit:   Positron   State: Alive
         Position[mm] Momentum[mrad]      Spin    |
 X:       -0.00000126   -0.00009028 -0.00000539  | t_particle [sec]:        0.00000000E+00  E_tot: 7.00729E+09
 Y:       -0.00000051   -0.00003931  0.00000109  | t_part-t_ref [sec]:      0.00000000E+00  PC:    7.00729E+09
 Z:        0.00000000    0.00000000  1.00000000  | (t_ref-t_part)*Vel [m]:  0.00000000E+00  Beta:  0.999999997
```

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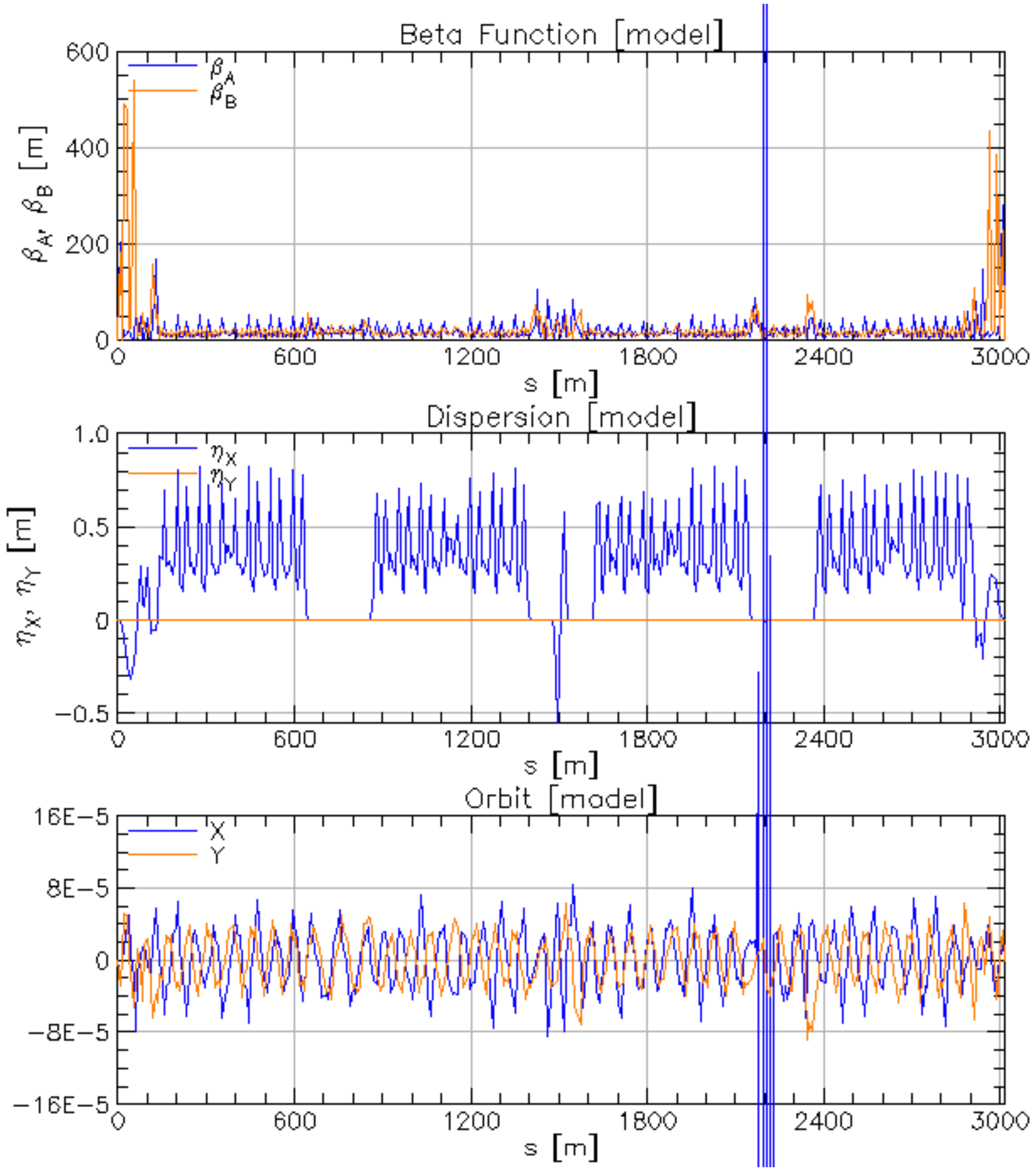
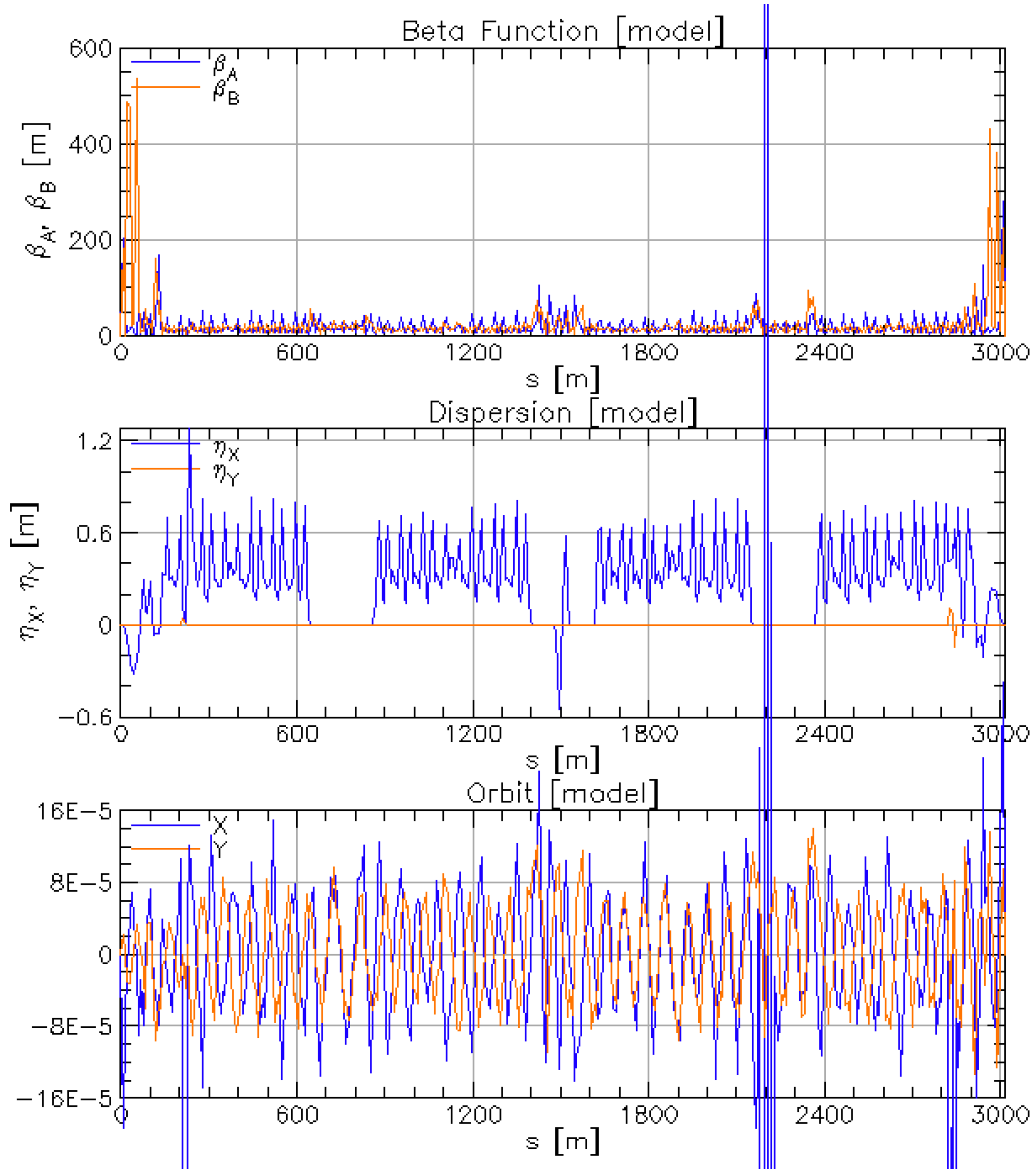
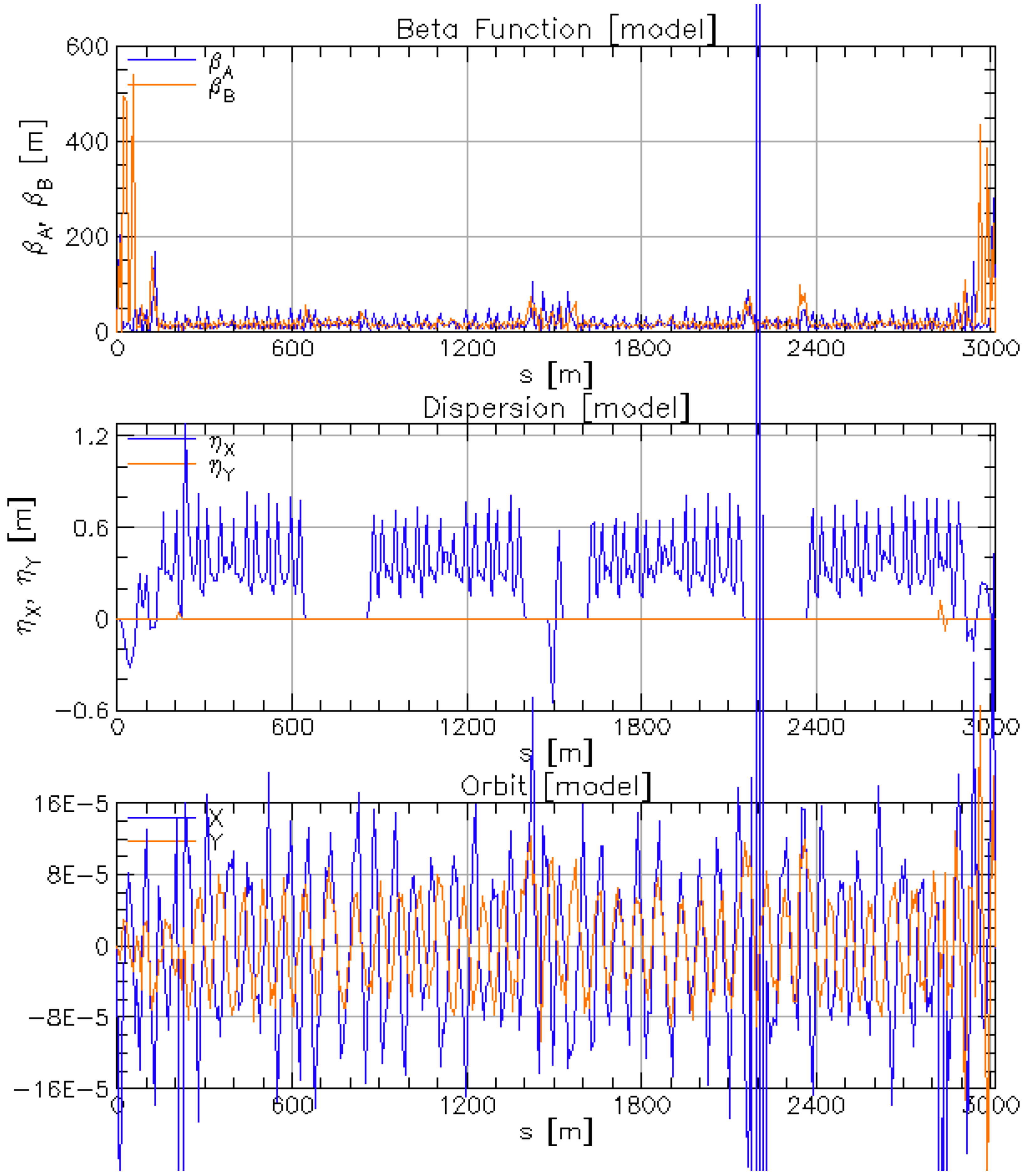


Original



Rot



Alternative Rot

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Rot

	X Model	X Design	Y Model	Y Design	
Q	45.777566	45.777566	44.446774	44.446774	! Tune
Chrom	1.593508	1.541611	1.622865	1.700876	! dQ/(dE/E)
J_damp	0.984214	0.983584	1.005265	1.005263	! Damping Partition #
Emittance	4.88965E-09	4.89356E-09	4.01654E-12	4.01059E-12	! Meters
Alpha_damp	1.75793E-04	1.75681E-04	1.79553E-04	1.79553E-04	! Damping per turn
Damping_time	5.72340E-02	5.72706E-02	5.60354E-02	5.60355E-02	! Sec

Alternative Rot

	X Model	X Design	Y Model	Y Design	
Q	45.851677	45.851677	44.544579	44.544579	! Tune
Chrom	1.593508	1.584082	1.622865	1.536385	! dQ/(dE/E)
J_damp	0.973110	0.972546	1.005193	1.005192	! Damping Partition #
Emittance	4.84923E-09	4.85242E-09	3.93024E-12	3.94263E-12	! Meters
Alpha_damp	1.73810E-04	1.73709E-04	1.79540E-04	1.79540E-04	! Damping per turn
Damping_time	5.78871E-02	5.79206E-02	5.60395E-02	5.60395E-02	! Sec

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