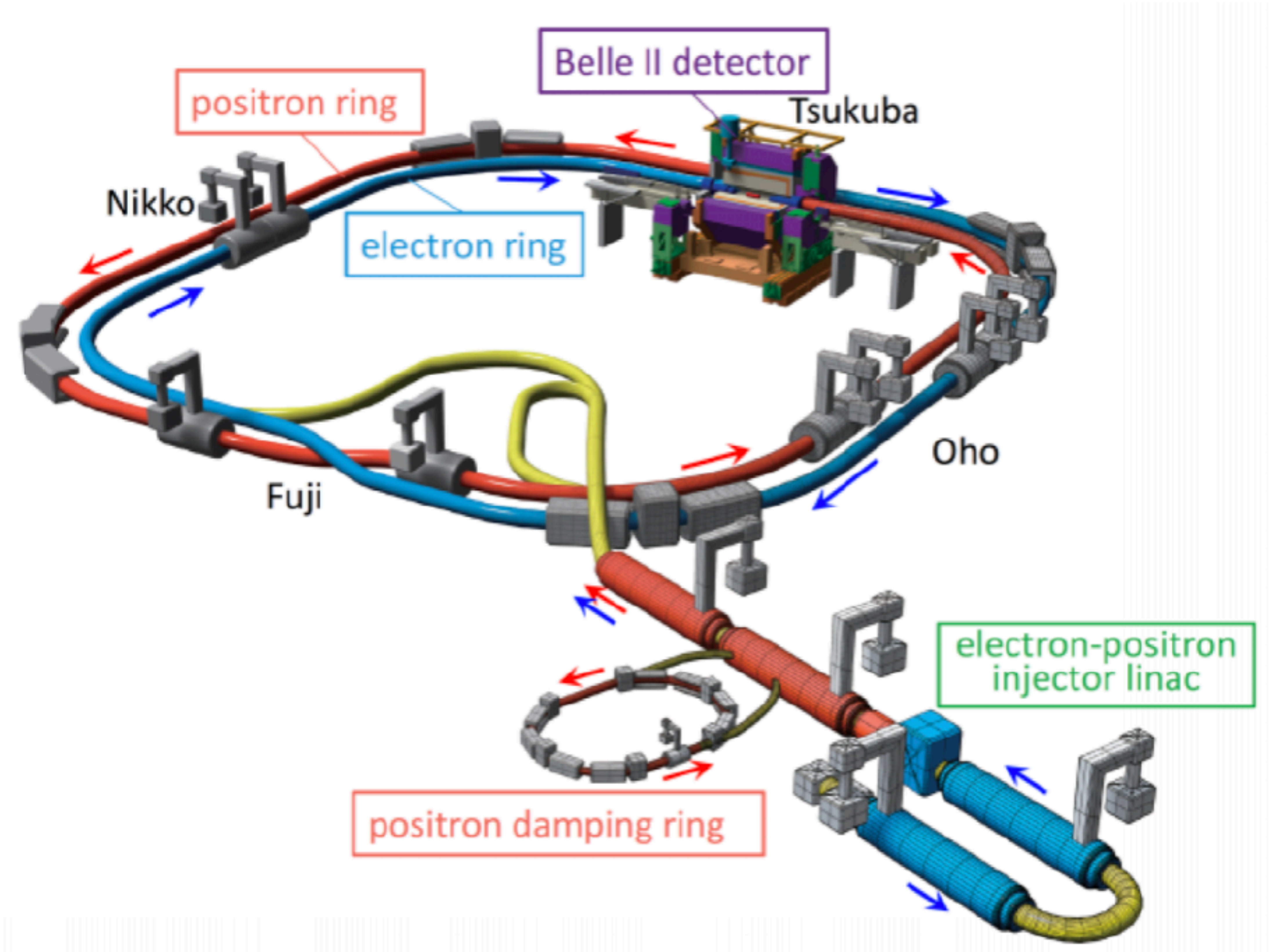
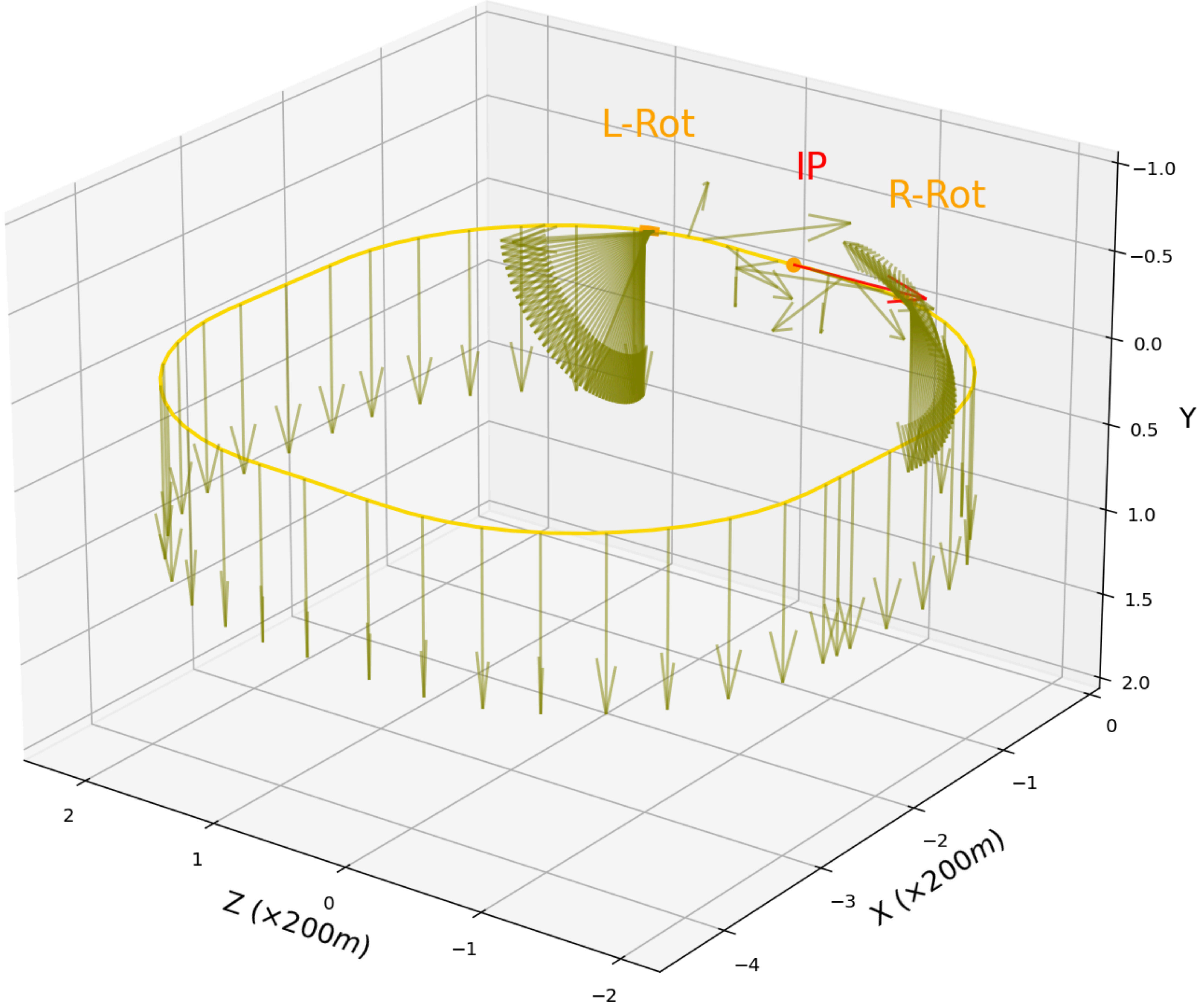
Spin Rotator Design for the SuperKEKB High Energy Ring in a Proposed Polarization Upgrade





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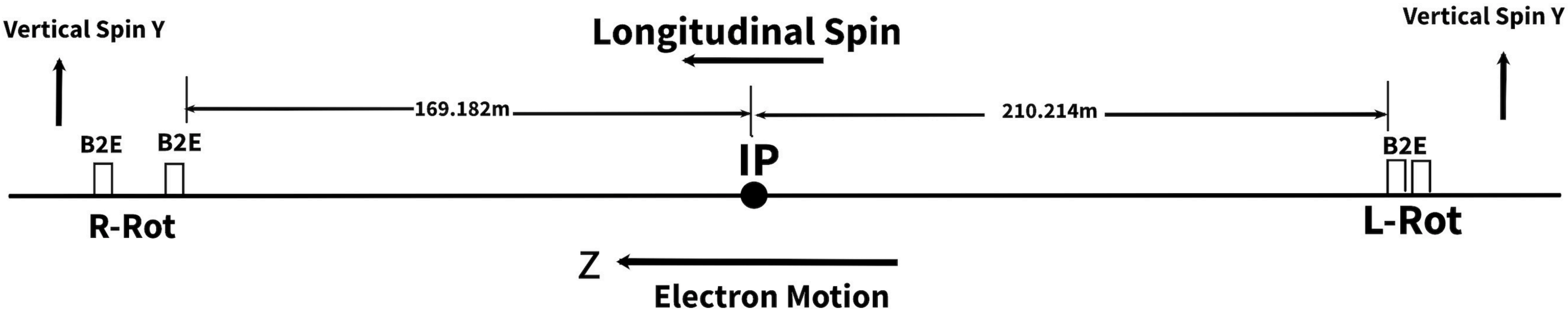
2021.10.19

Spin Rotator



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

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

Our simulation is running by the positron, which runs reversely in the HER and the ring is viewed from downward to upward

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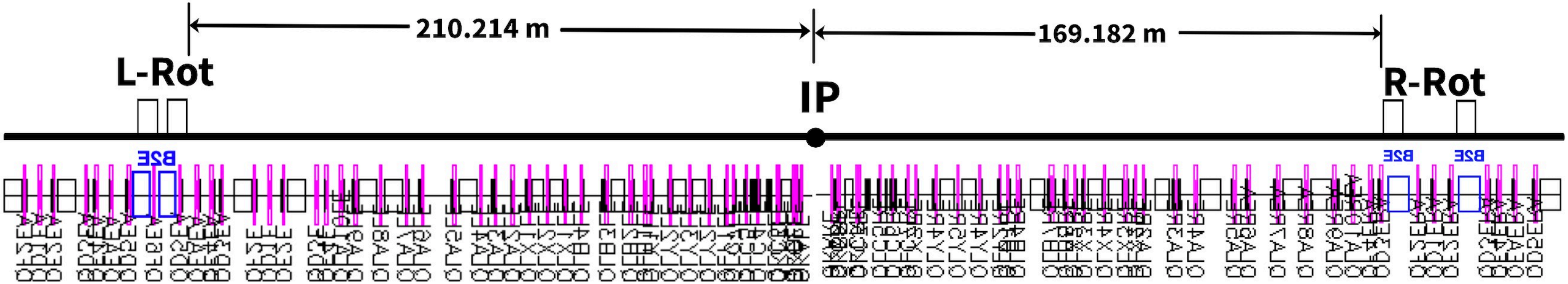

(Lab View)

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

~212.15˚ clockwise in the x-z plane

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

~203.32˚ clockwise in the x-z plane

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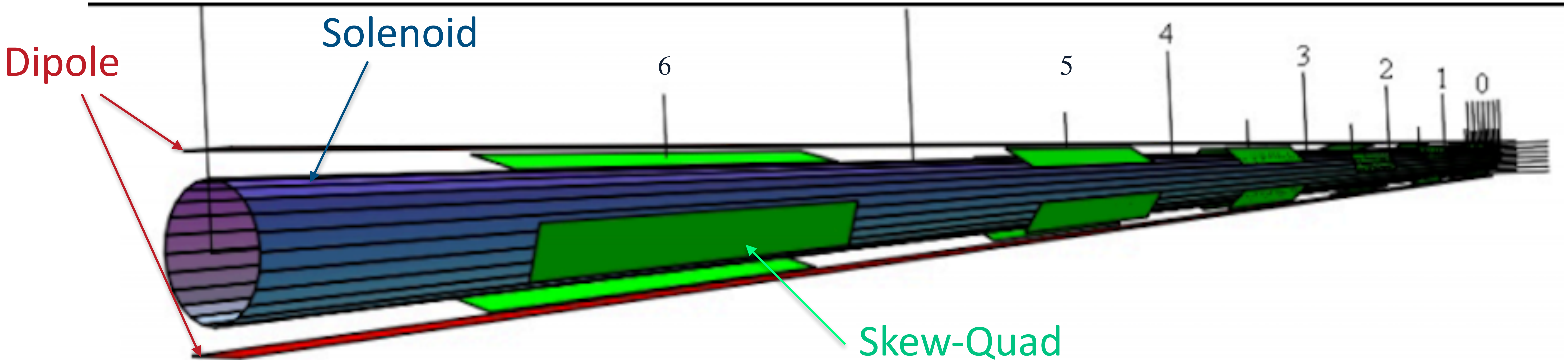
Rotator Magnet Structure

- 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 to keep the geometry
- Install 6 skew-quadruple on top of each rotator section to compensate for the x-y plane coupling caused by solenoids



Hkick Simulation

Rotator modelling requires a combination of dipole and solenoid-quadrupole

- Bmad has the solenoid-quadrupole but does not have the 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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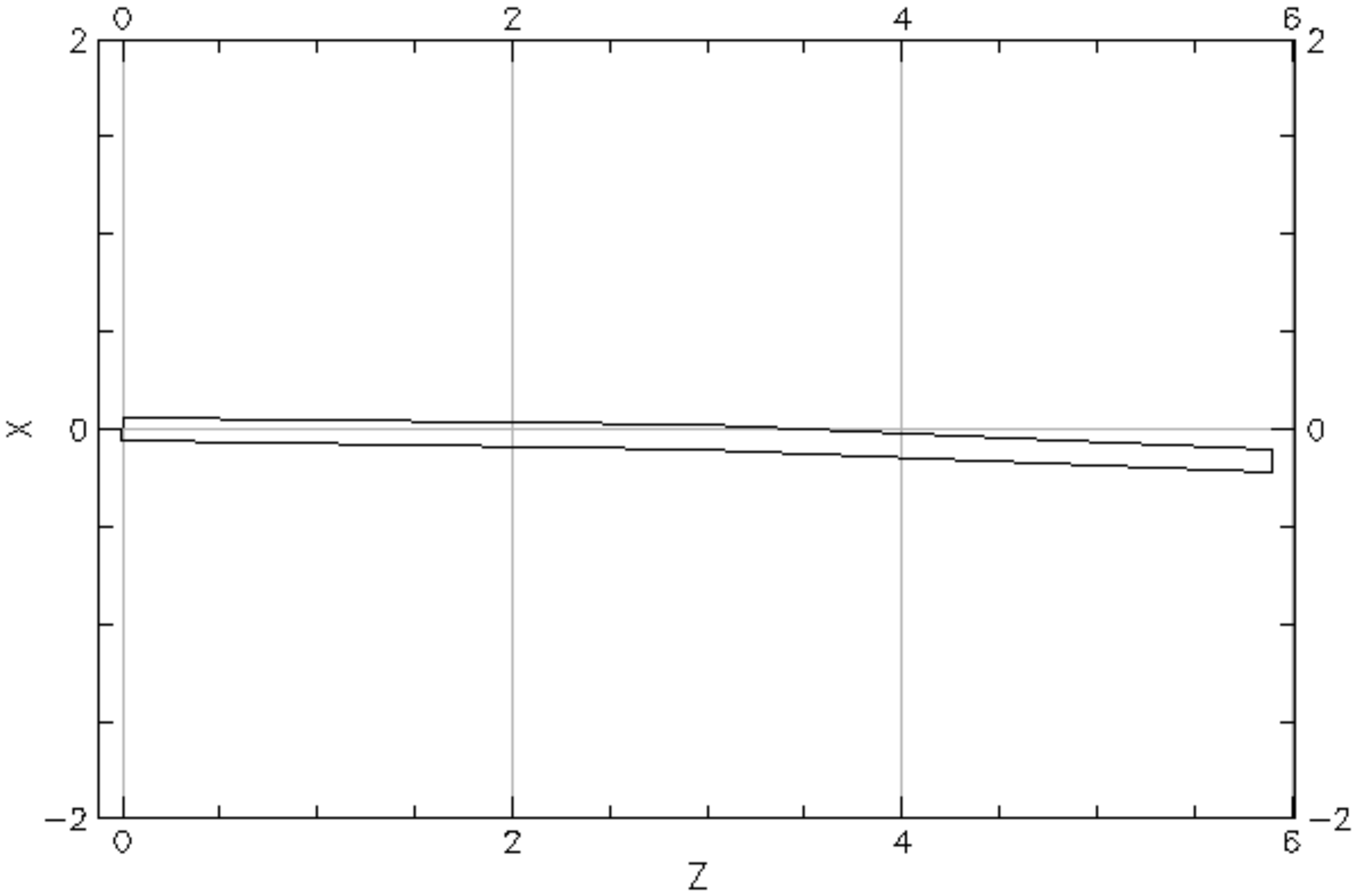
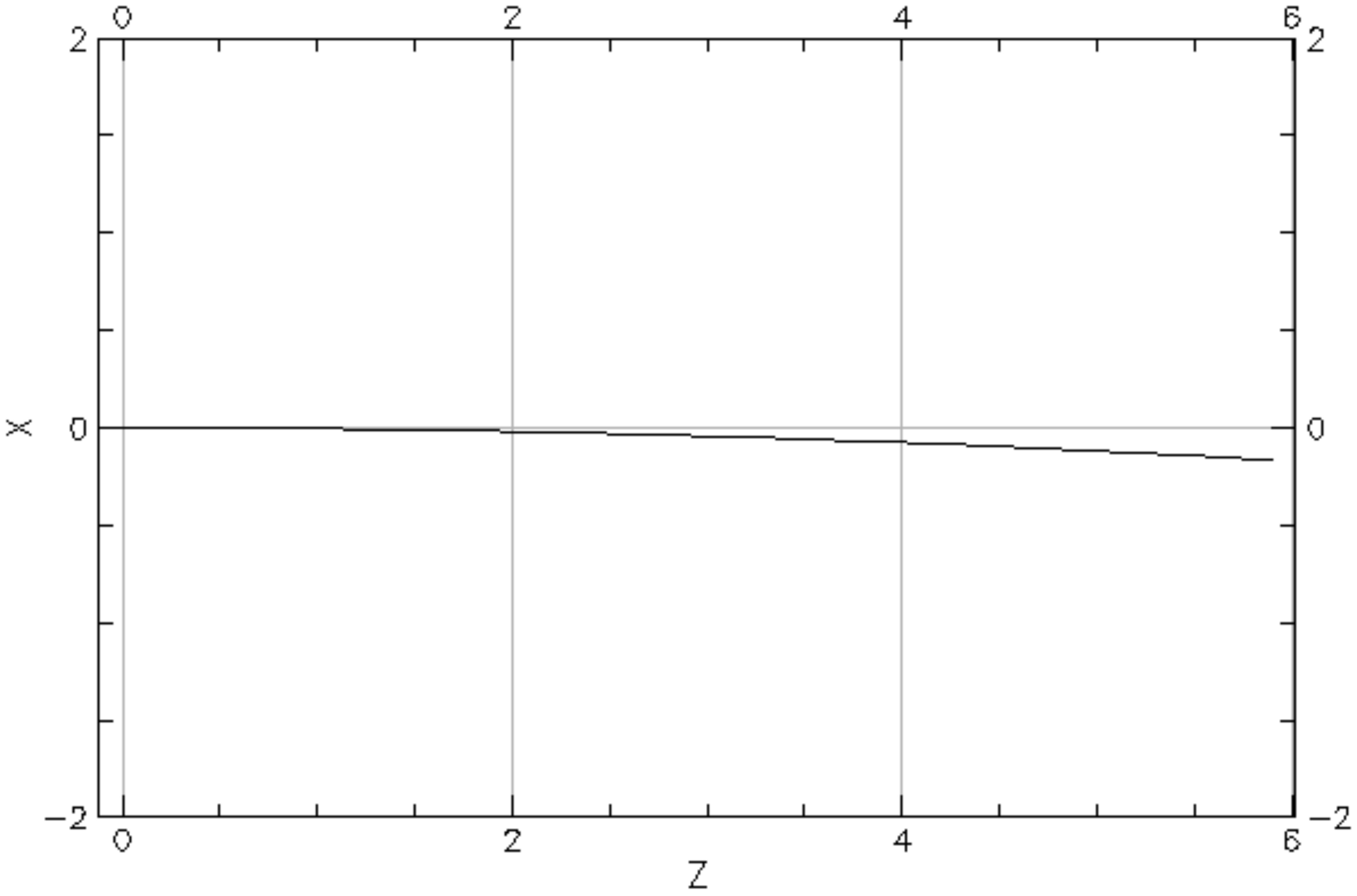
Comparison of floor coord between the B2E and the Hkick after fixing the floor coord and orbit



Original B2E



Hkick(6-piece sliced)

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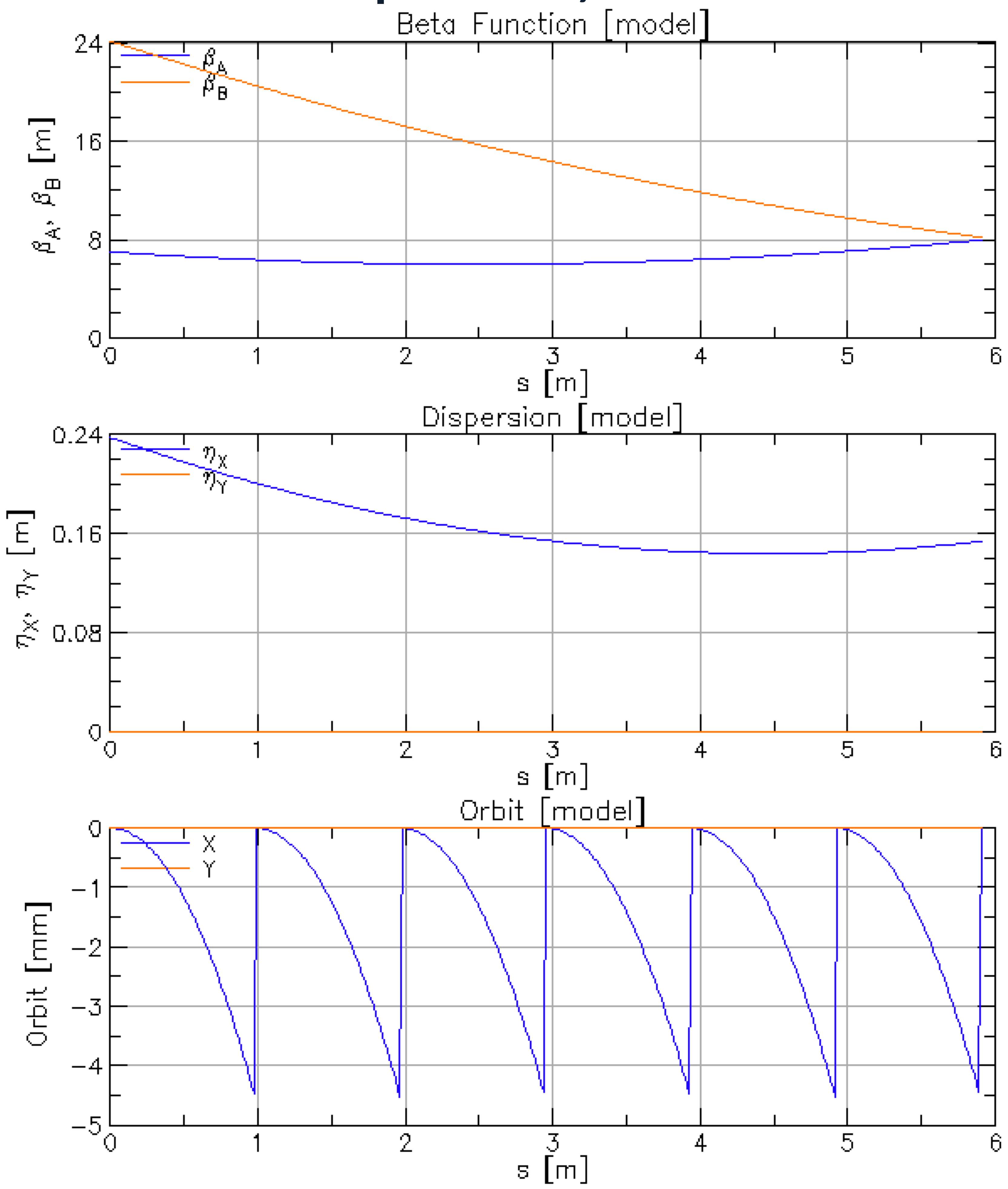
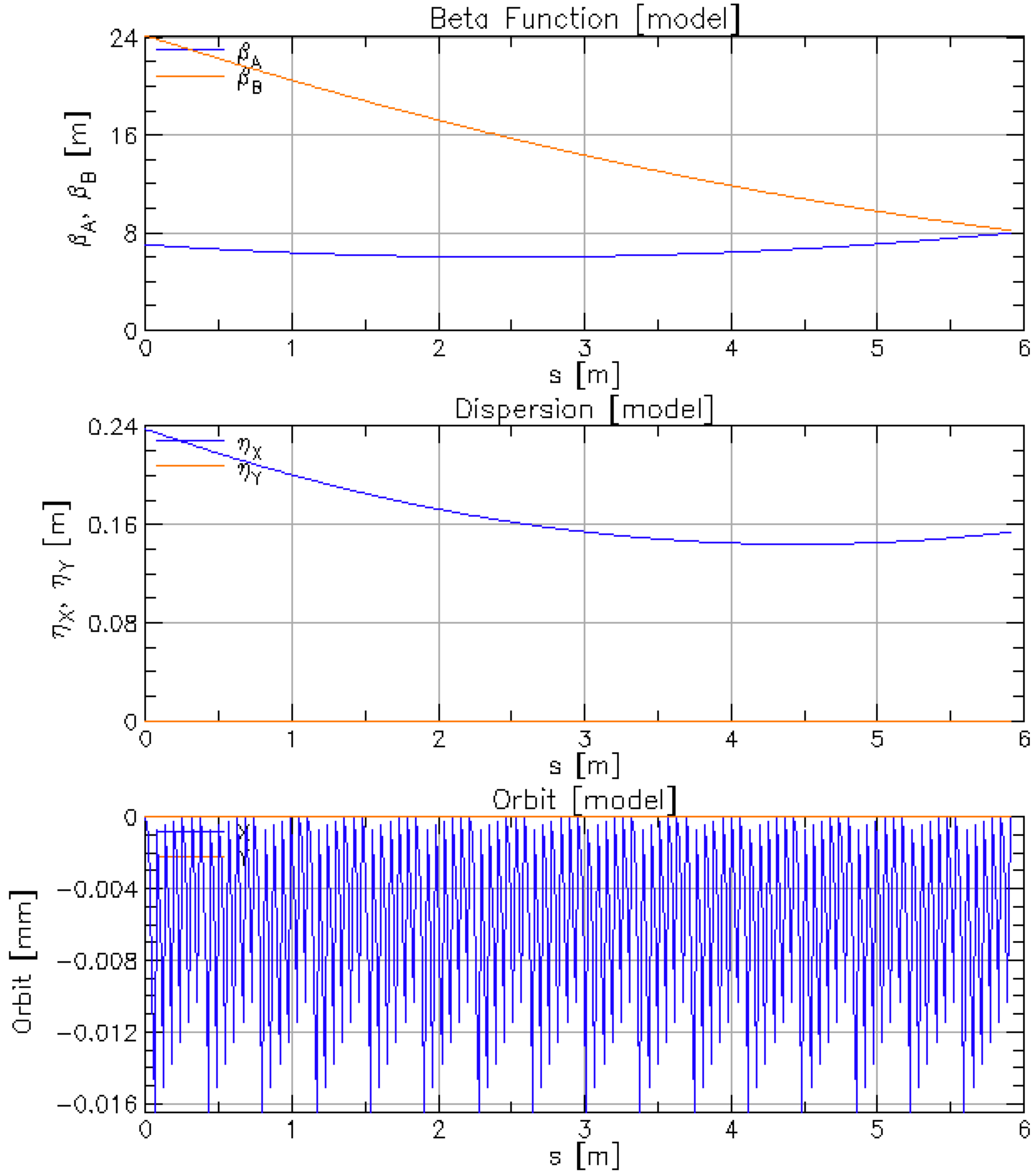
Slice Model

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 Rotation in B2E

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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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 (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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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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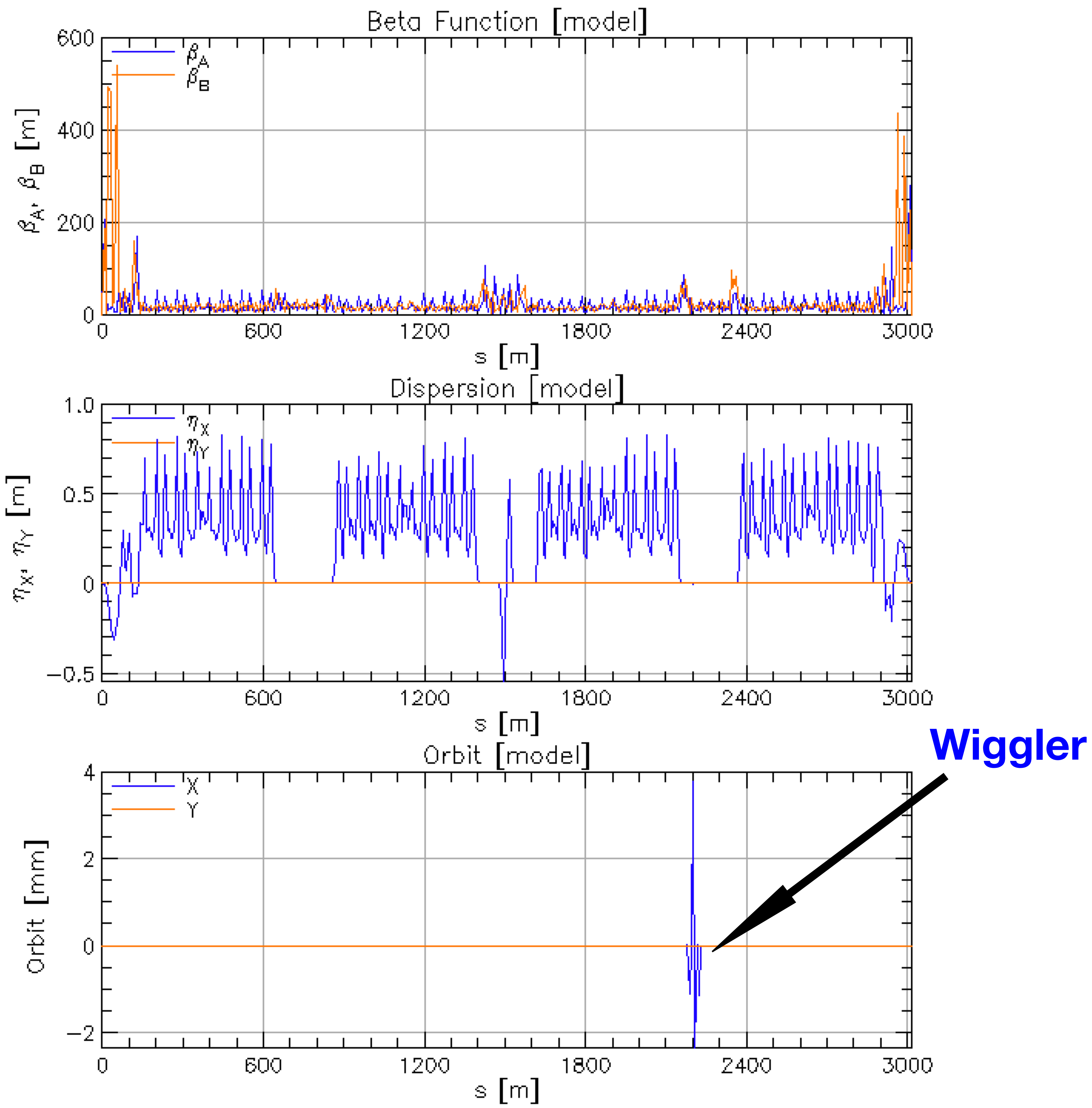
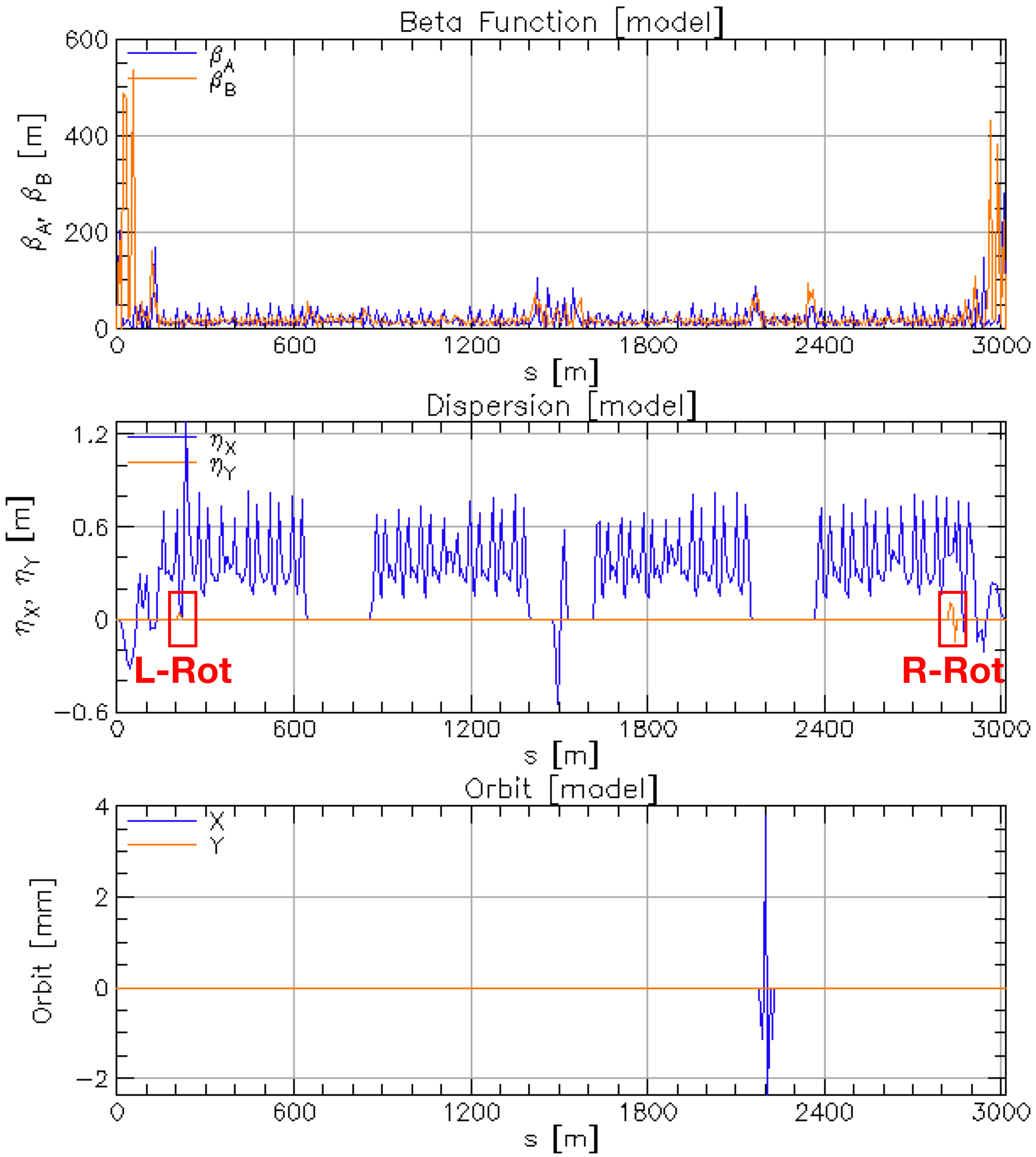
Comparison of Full Lattice (positron simulation)





Original

Rot

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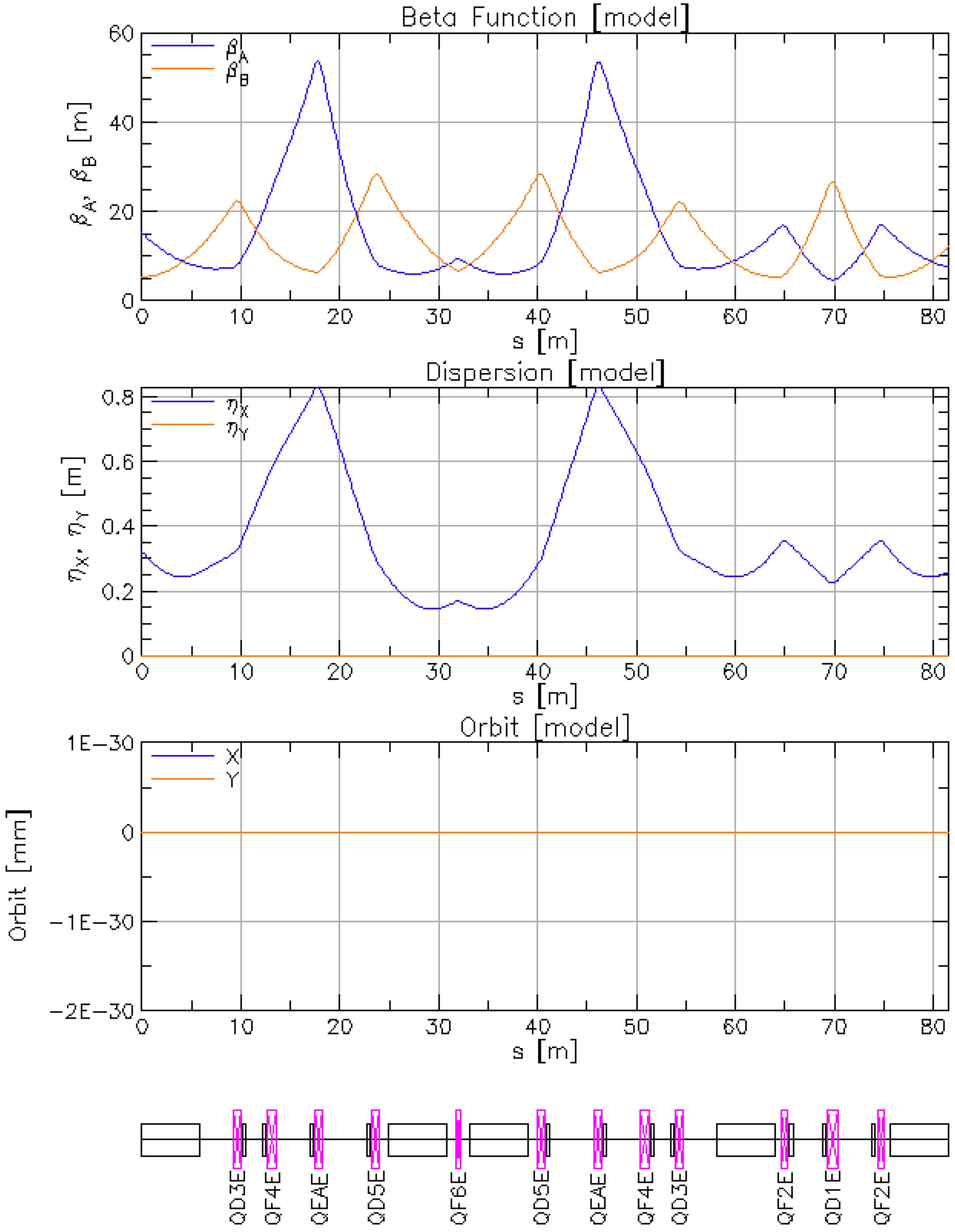
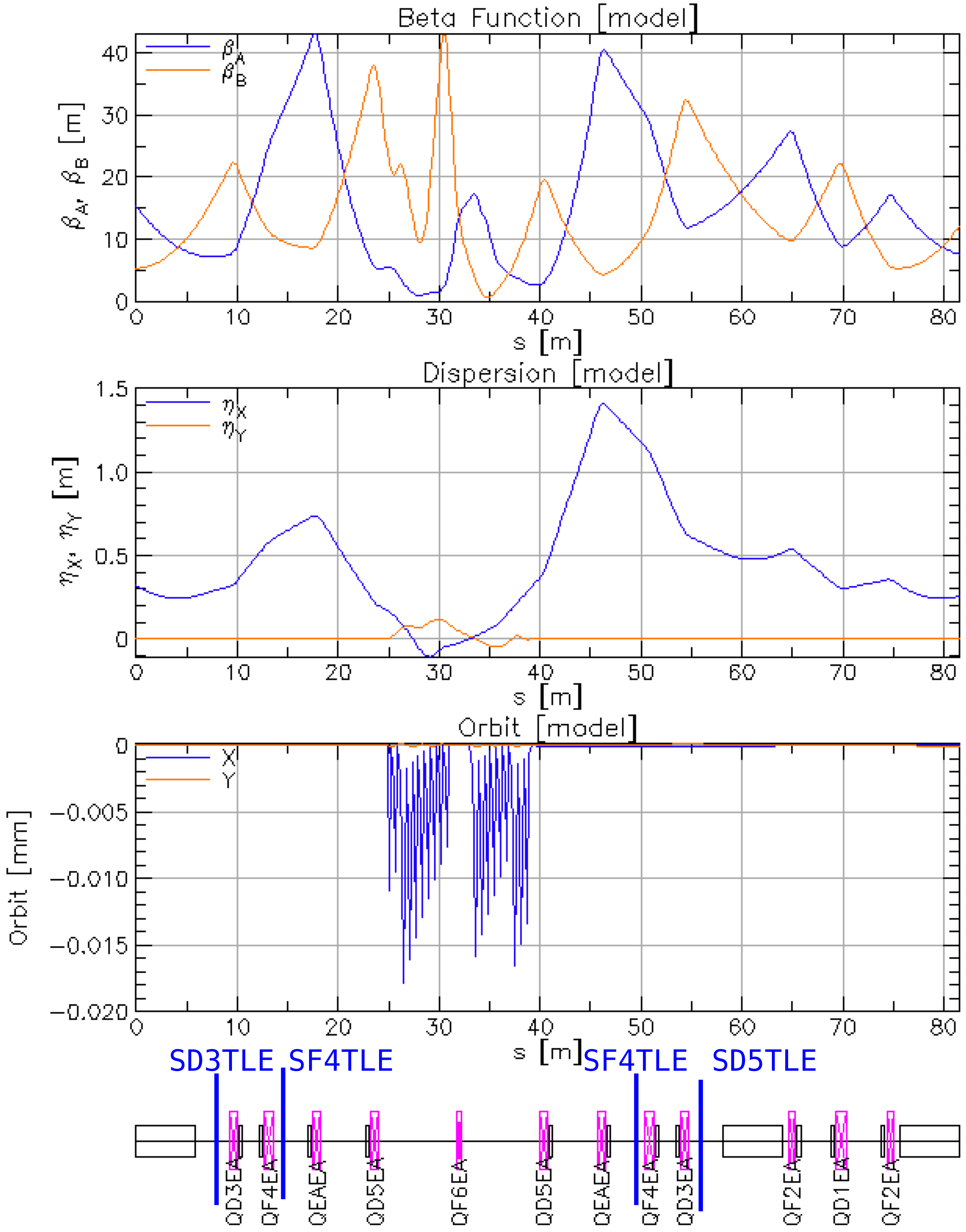
Comparison at L-Rot Region (Positron simulation)



Original



L-Rot

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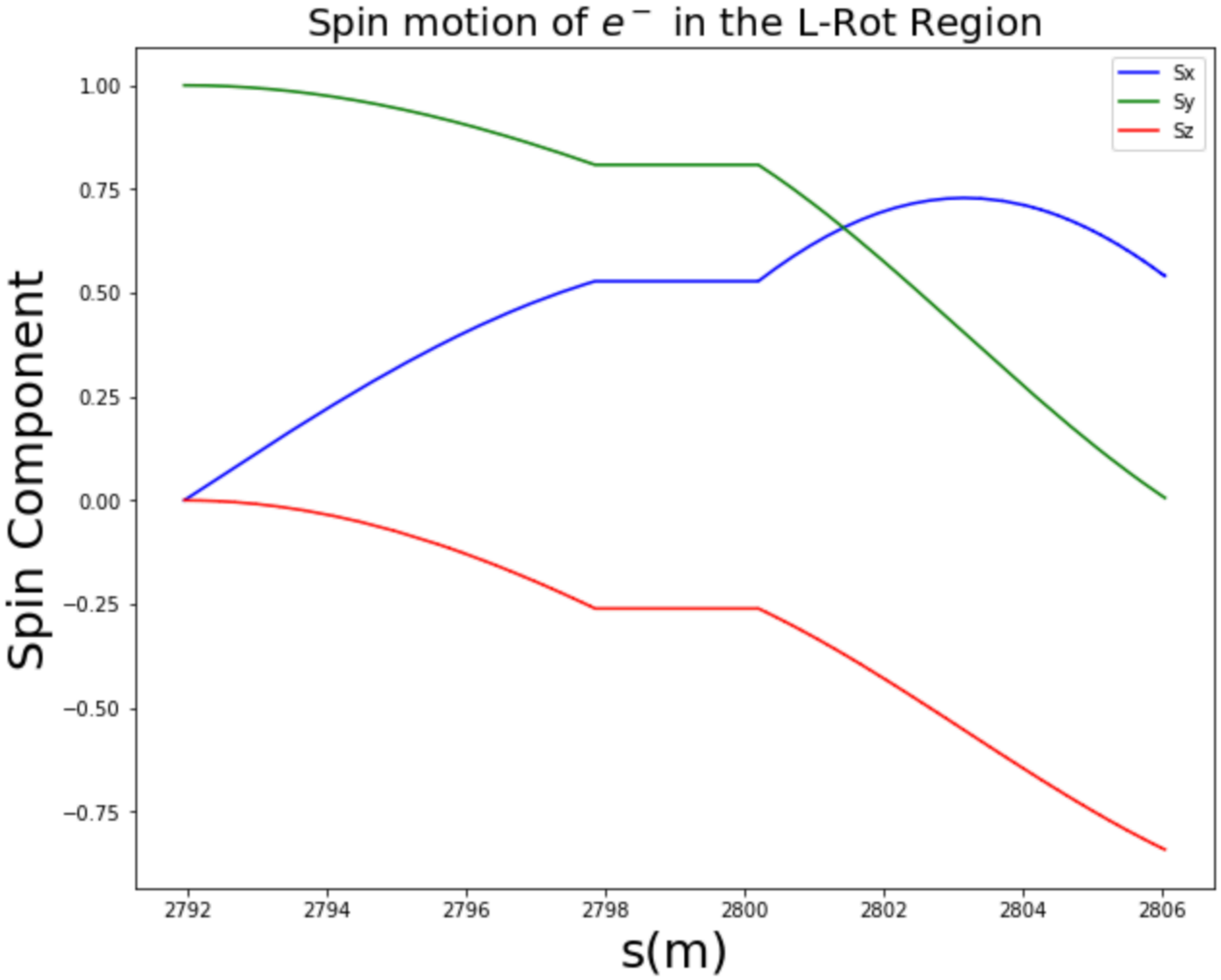

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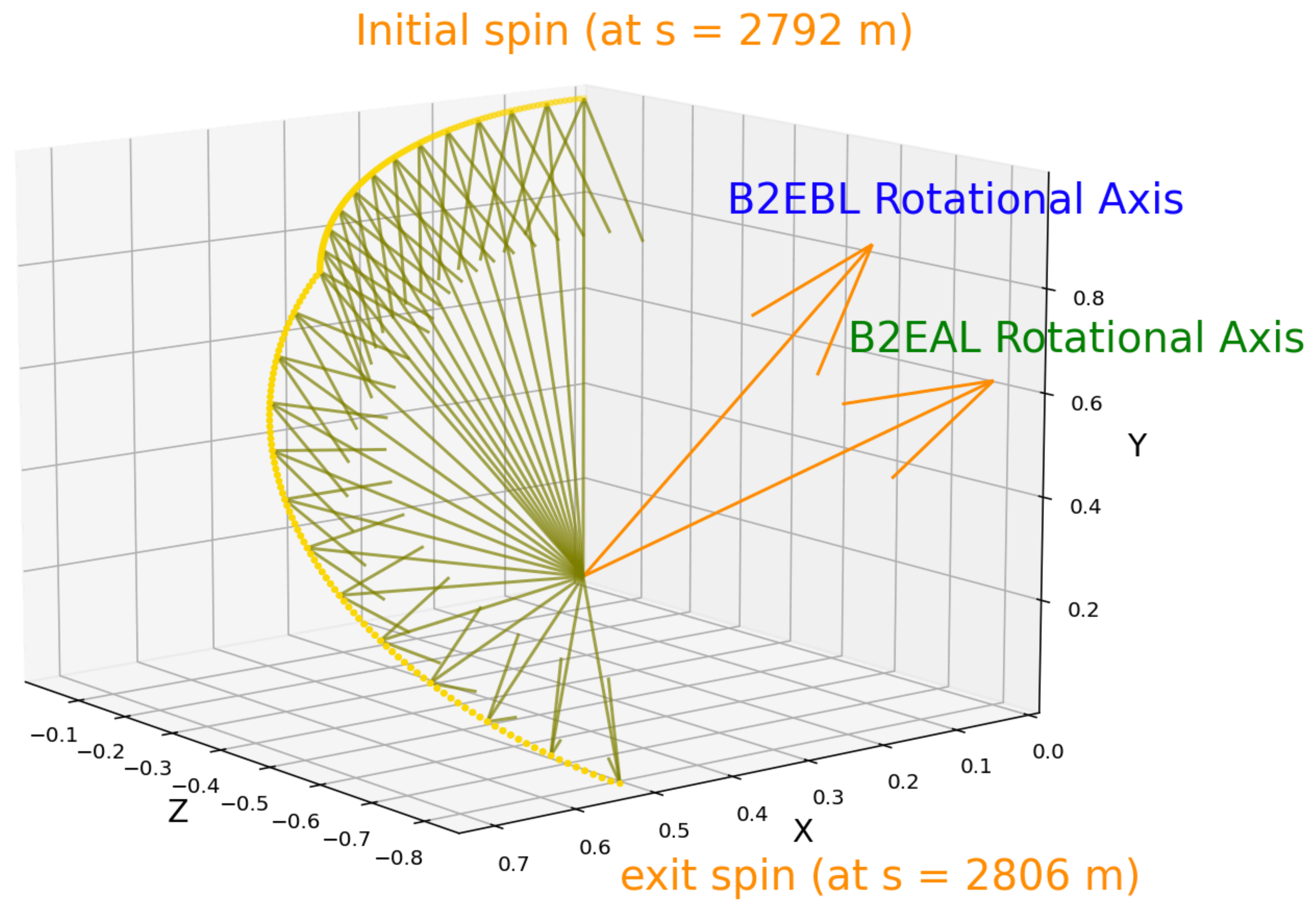
Spin Motion of e^- (rest frame) in the L-Rot Region



L-Rot Solenoid Strength

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

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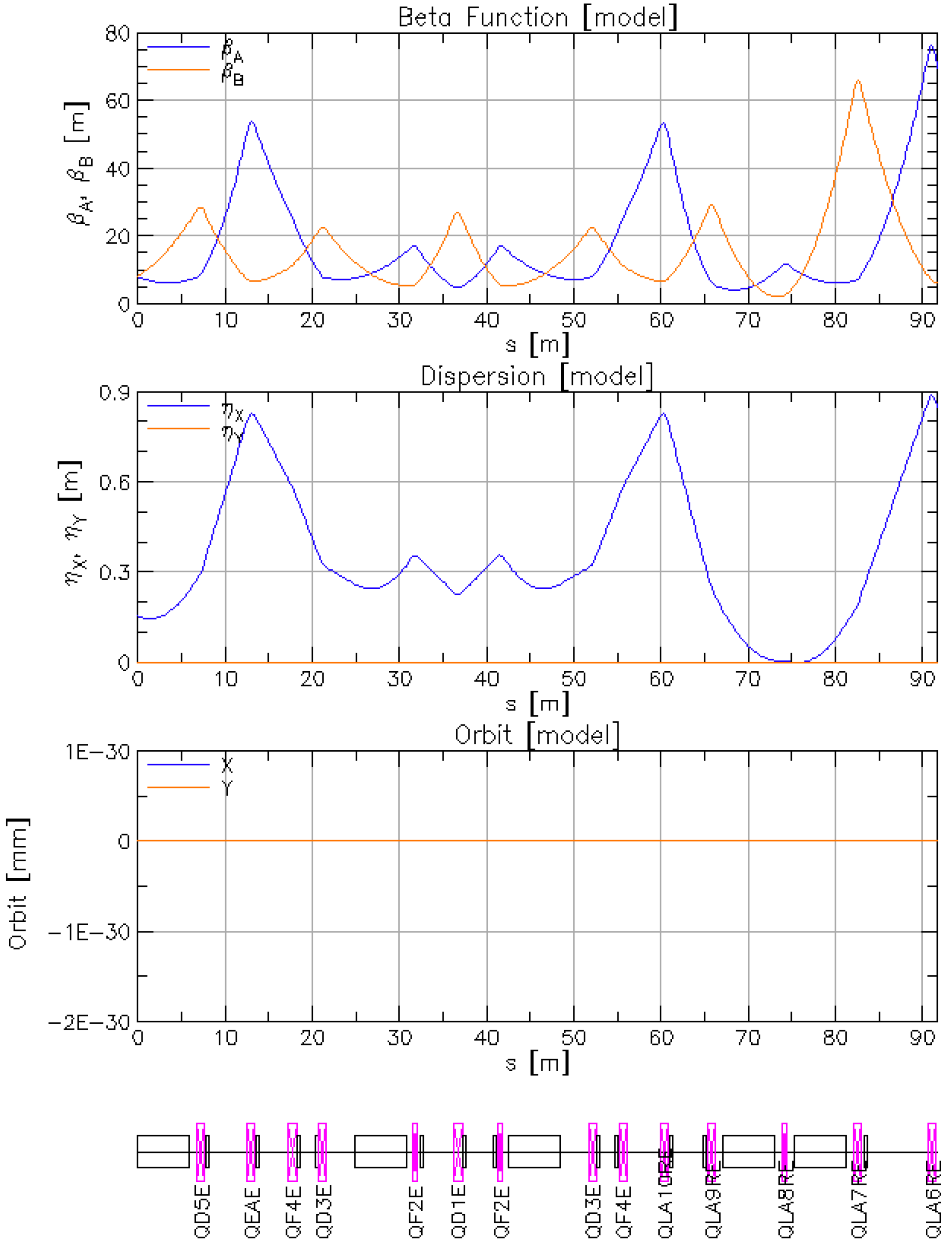
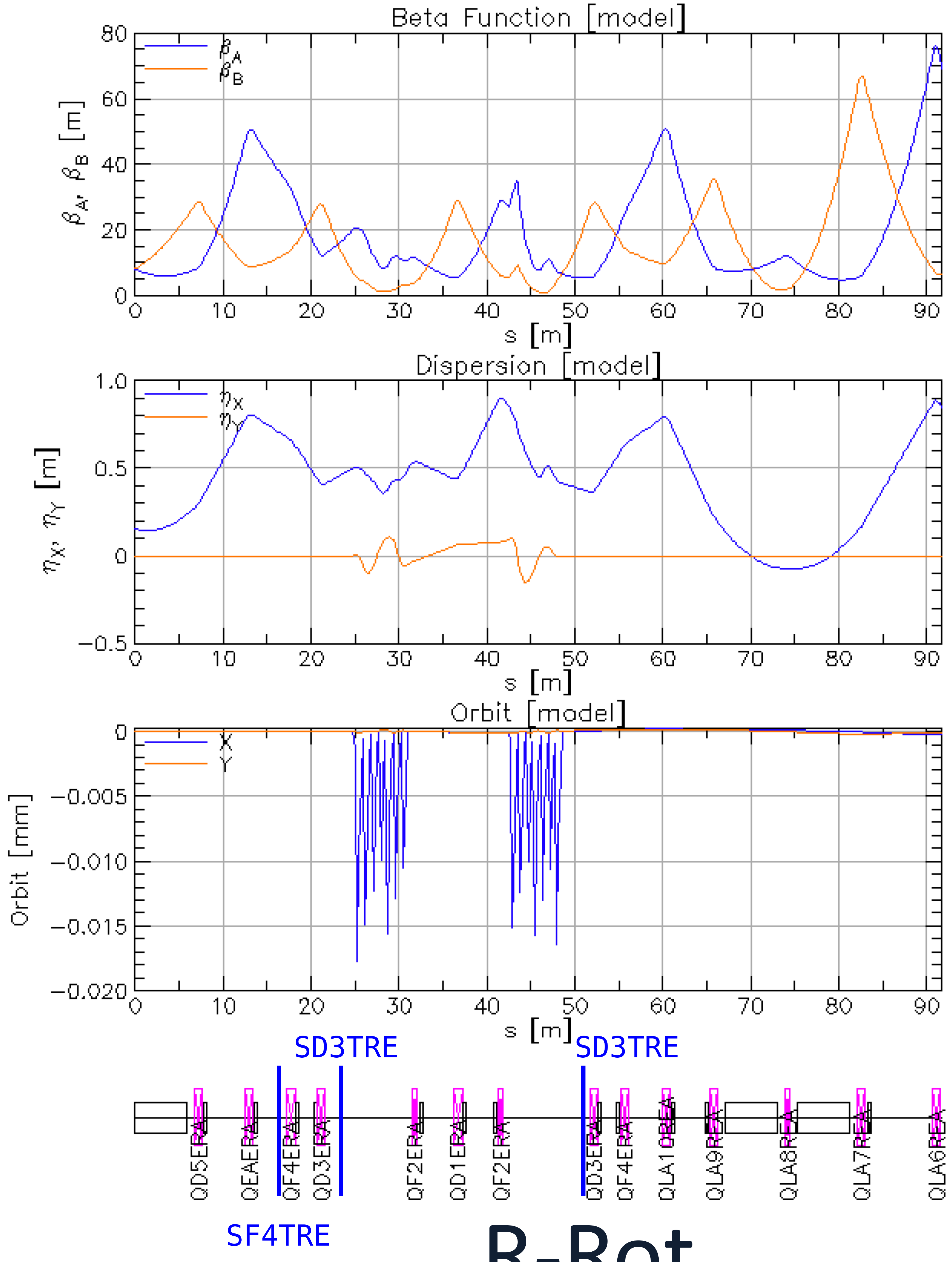
Comparison at R-Rot Region(Positron simulation)



Original



R-Rot

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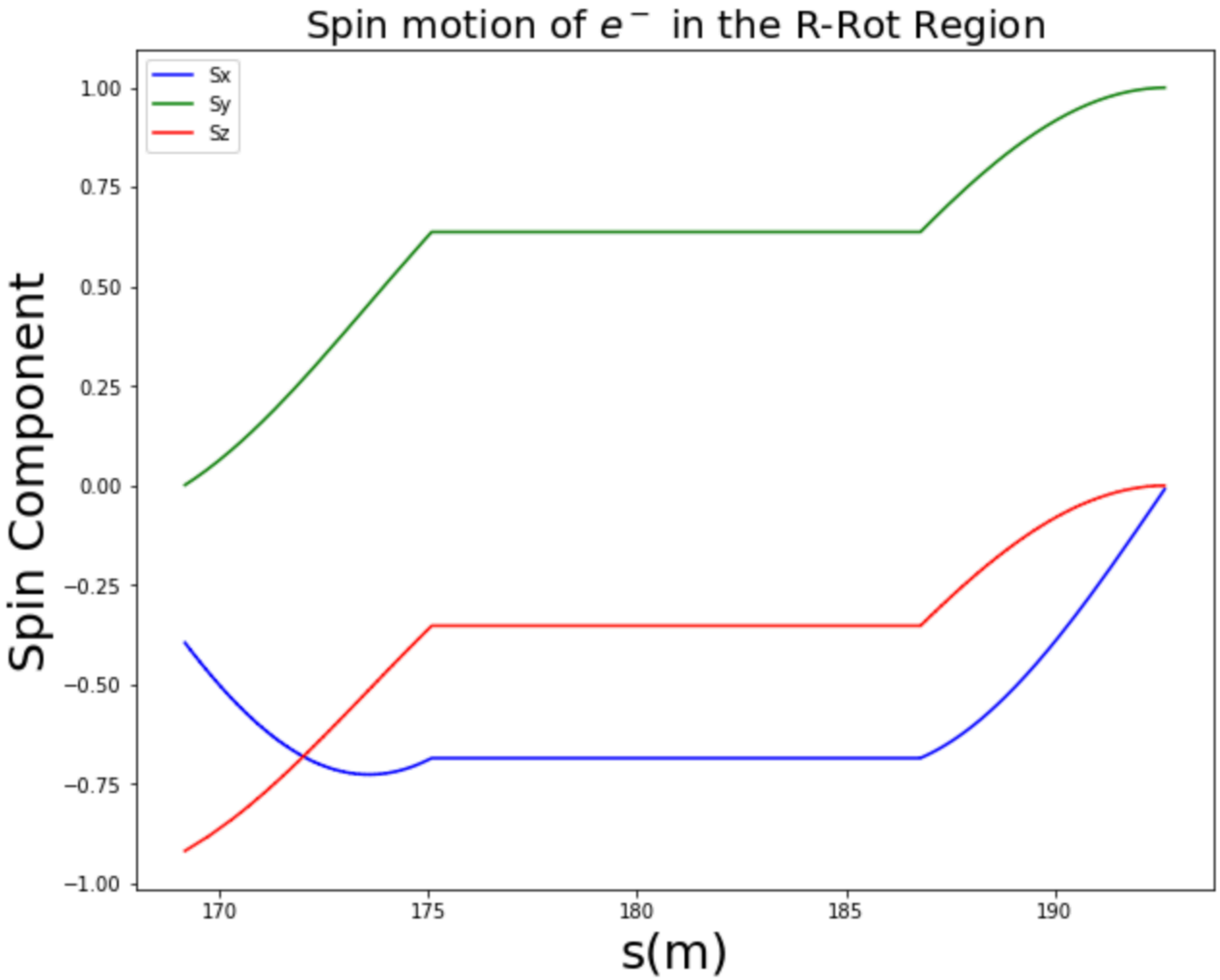

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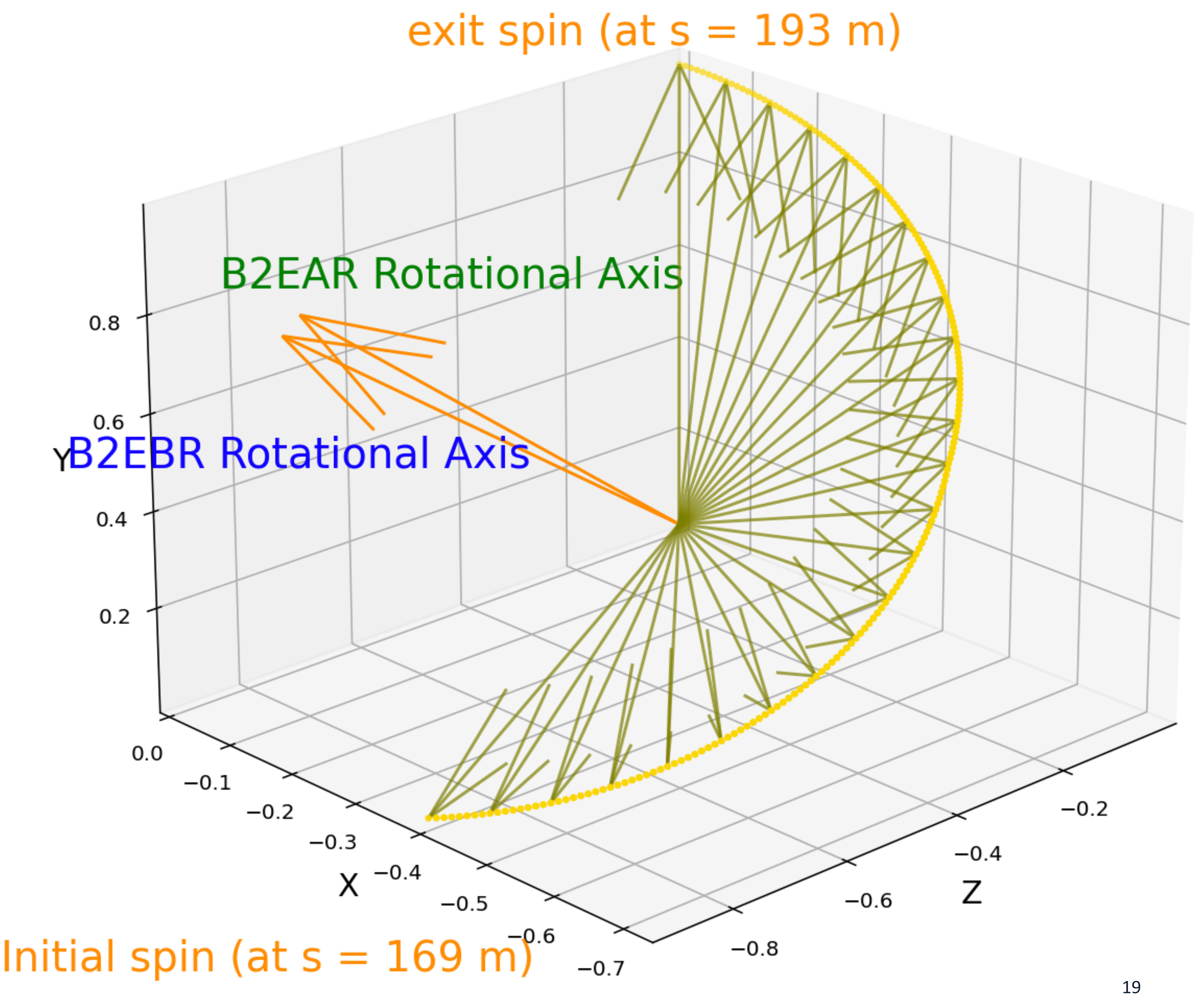
Spin Motion of e^- (rest frame) in the R-Rot Region



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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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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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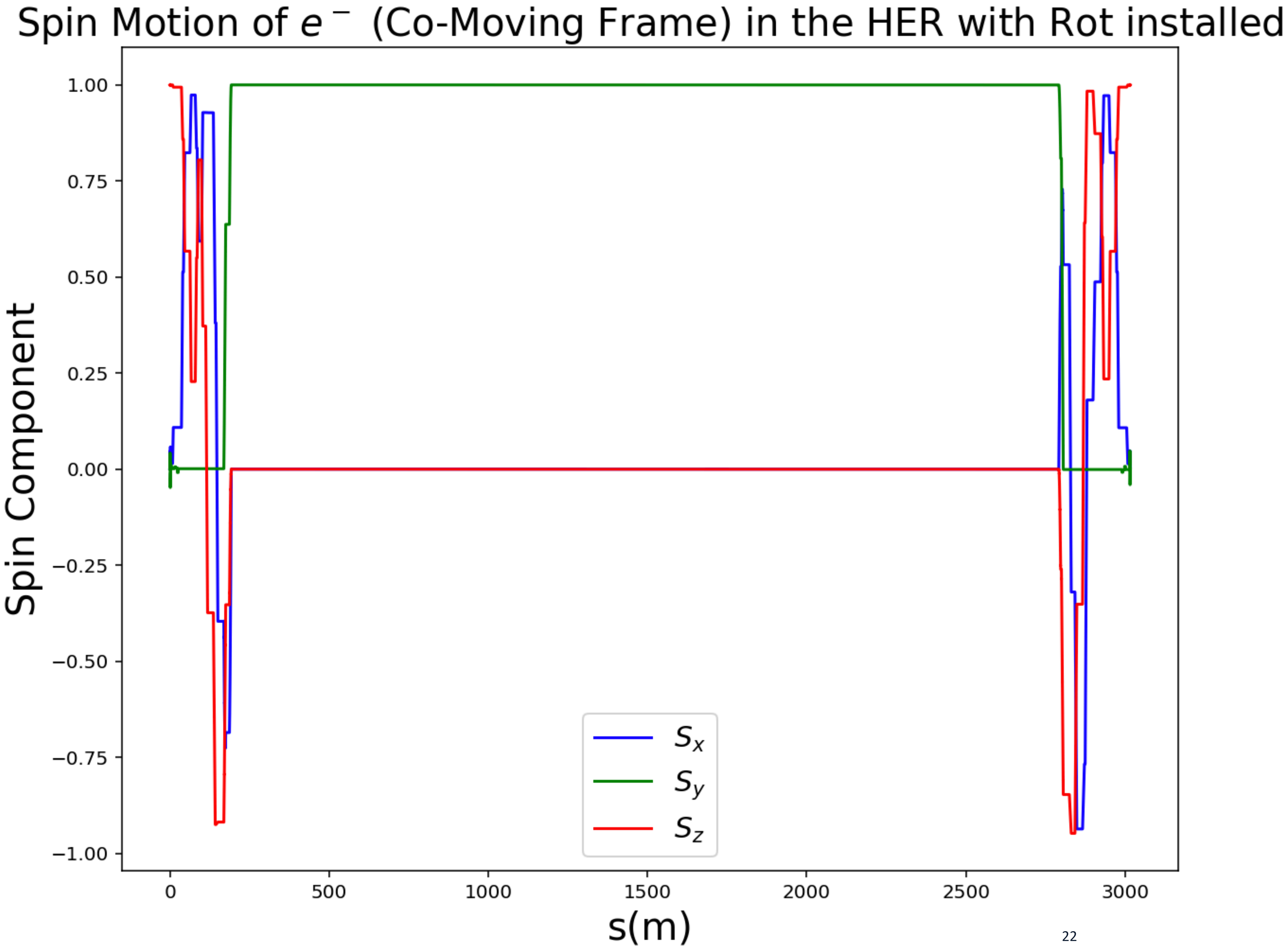

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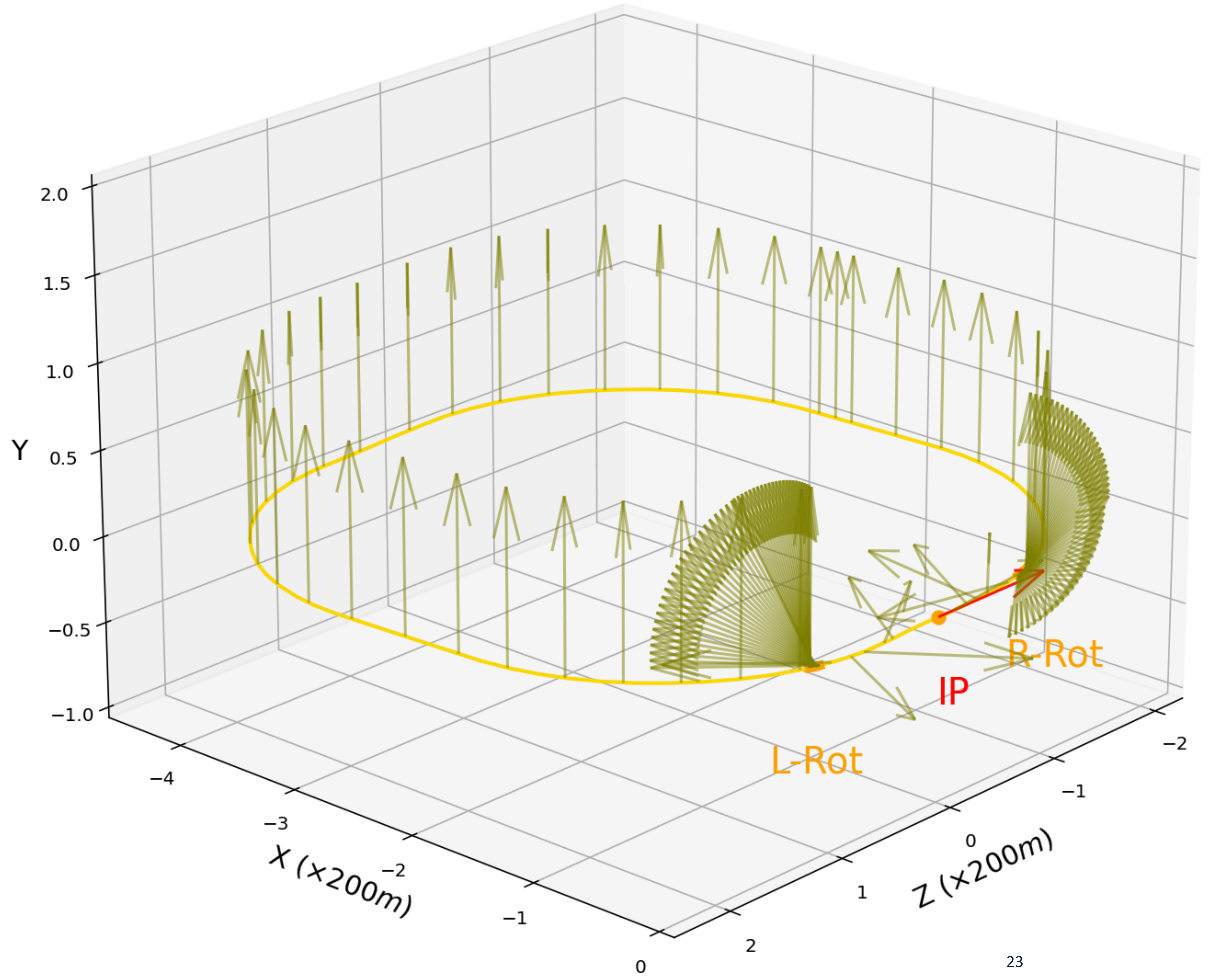
Spin Motion of e^- (Lab Frame) in the SuperKEKB HER with Spin Rotator Installed



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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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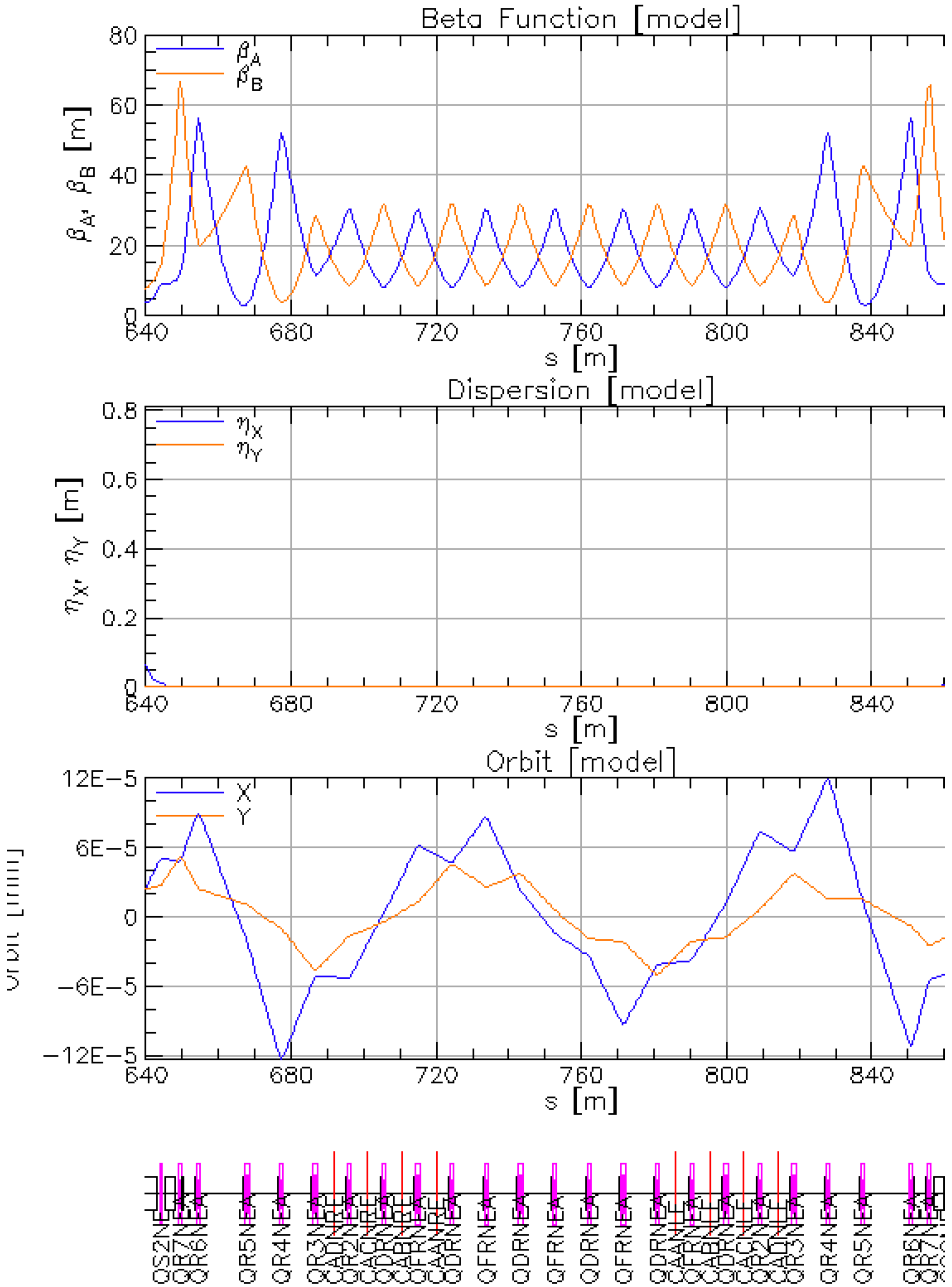
Matching the Tune Value (in progress)



Fitting target: Q_x, Q_y

Constraints: Matching the Twiss parameters at the exit of the straight section ($\beta_{x,y}$, $\alpha_{x,y}$)

8 variables: QR*NE(6 different Quadruopole pairs), QDRNE, QFRNE

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Future Steps

- Fixing the Tune value with tuning the ring quads at the straight section

- Tracking Studies (Long_Term_Tracking)

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Appendix

The normalized integrated multipole K_nL (equivalent to k_n in SAD) can be used when specifying magnetic multipole components

$$K_nL \equiv \frac{qB_nL}{P_0}$$

- where q is the charge of the reference particle (in units of the elementary charge), L is the element length, and P_0 is the reference momentum (in units of eV/c)
- In our case, K_nL can be approximately calculated by $K_nL \simeq \frac{3B_nL}{70}$

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Spin Dynamics

The spin motion in external EM field is described by Thomas-BMT equation (ignoring the E field):

$$\frac{d\vec{s}}{dt} = \overrightarrow{\Omega} \times \overrightarrow{S} = \frac{q}{m\gamma} \overrightarrow{S} \times \left((1 + a\gamma) \overrightarrow{B}_{\perp} + (1 + a) \overrightarrow{B}_{//} \right)$$

q = -e for the electron

$$\frac{d\vec{s}}{ds} = \frac{d\vec{s}}{dt}\frac{dt}{ds} = \frac{1}{v}\frac{d\vec{s}}{dt} = \frac{e}{p}\left((1 + a\gamma) \overrightarrow{B}_{\perp} + (1 + a) \overrightarrow{B}_{//} \right) \times \overrightarrow{S}$$

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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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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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

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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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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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