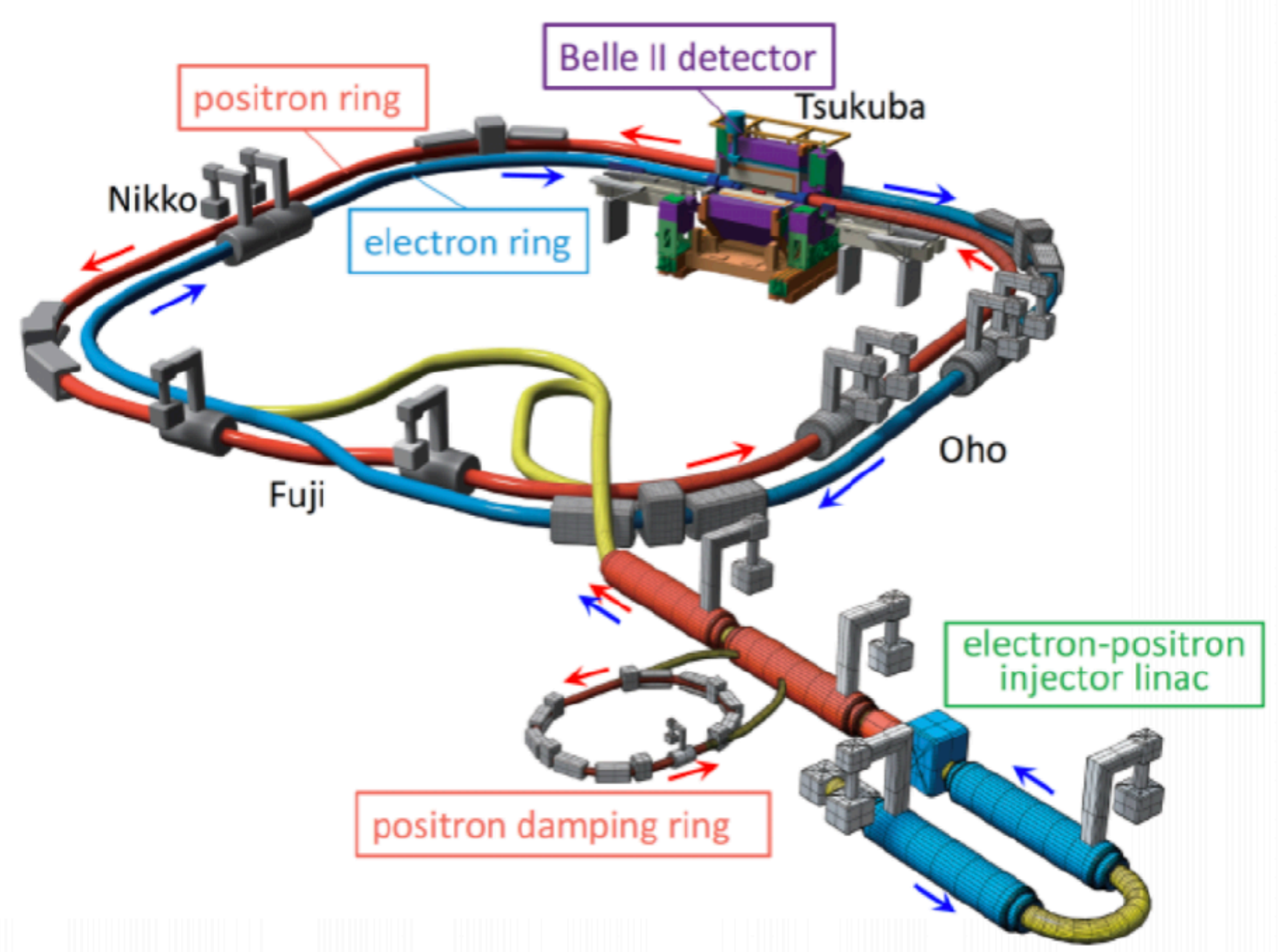
Spin Rotator Design for the SuperKEKB High Energy Ring in a Proposed Polarization Upgrade



Yuhao Peng

2021.09.27

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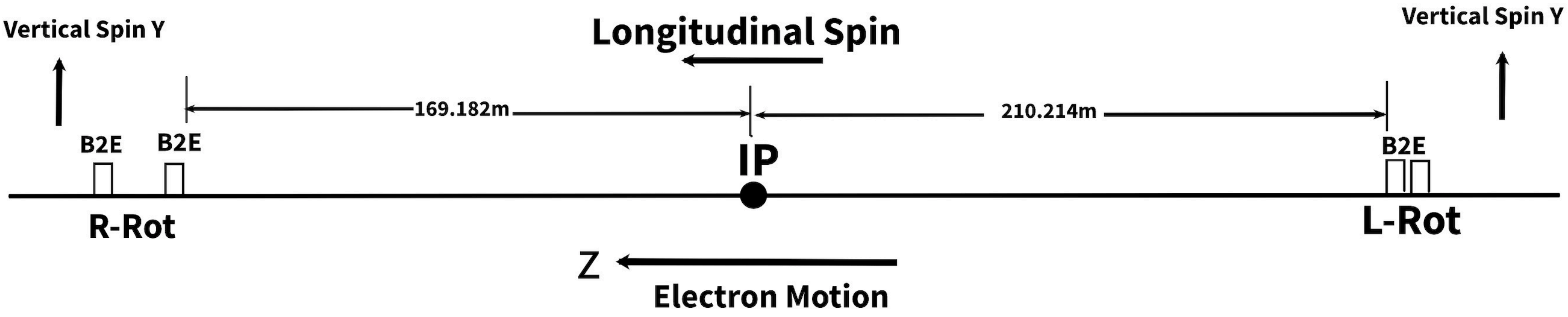
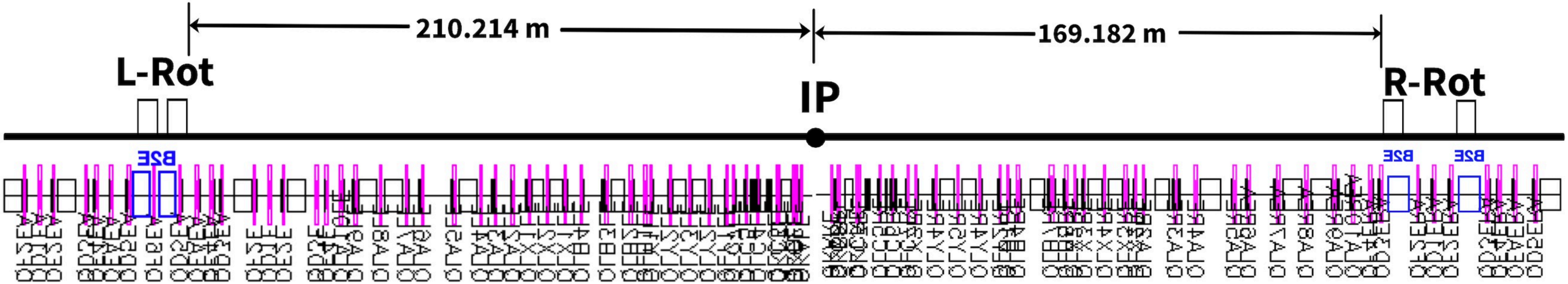
Spin Rotator



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

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



(Viewed from upward to downward)

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**:

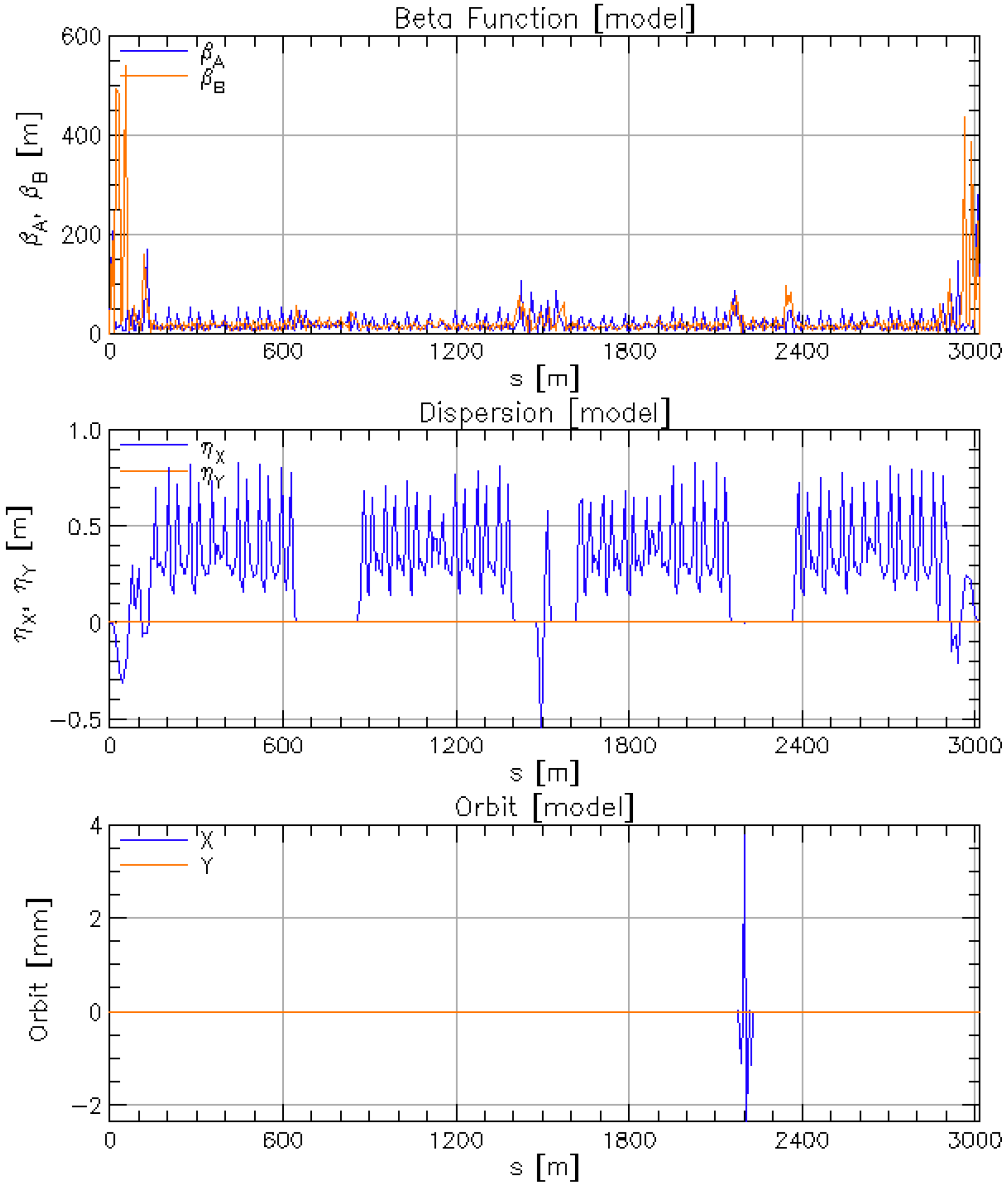
~203.32˚ clockwise in the x-z plane

Constraints of the Design

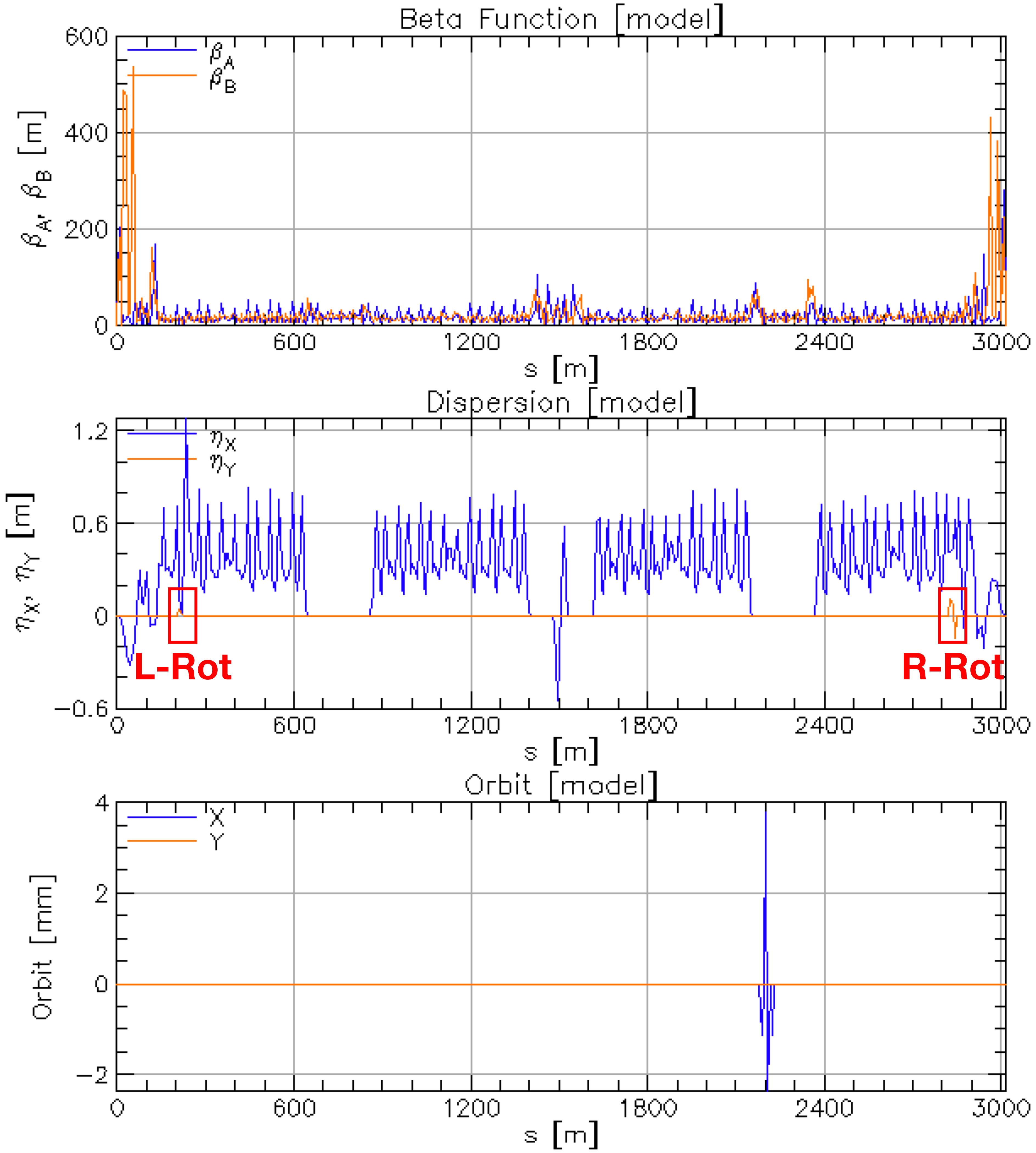
- **Transparency**: Need to maintain the original **beam dynamics,** make the spin rotator transparent to the ring as much as possible

- 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

Comparison of Full Lattice



Original



Rot

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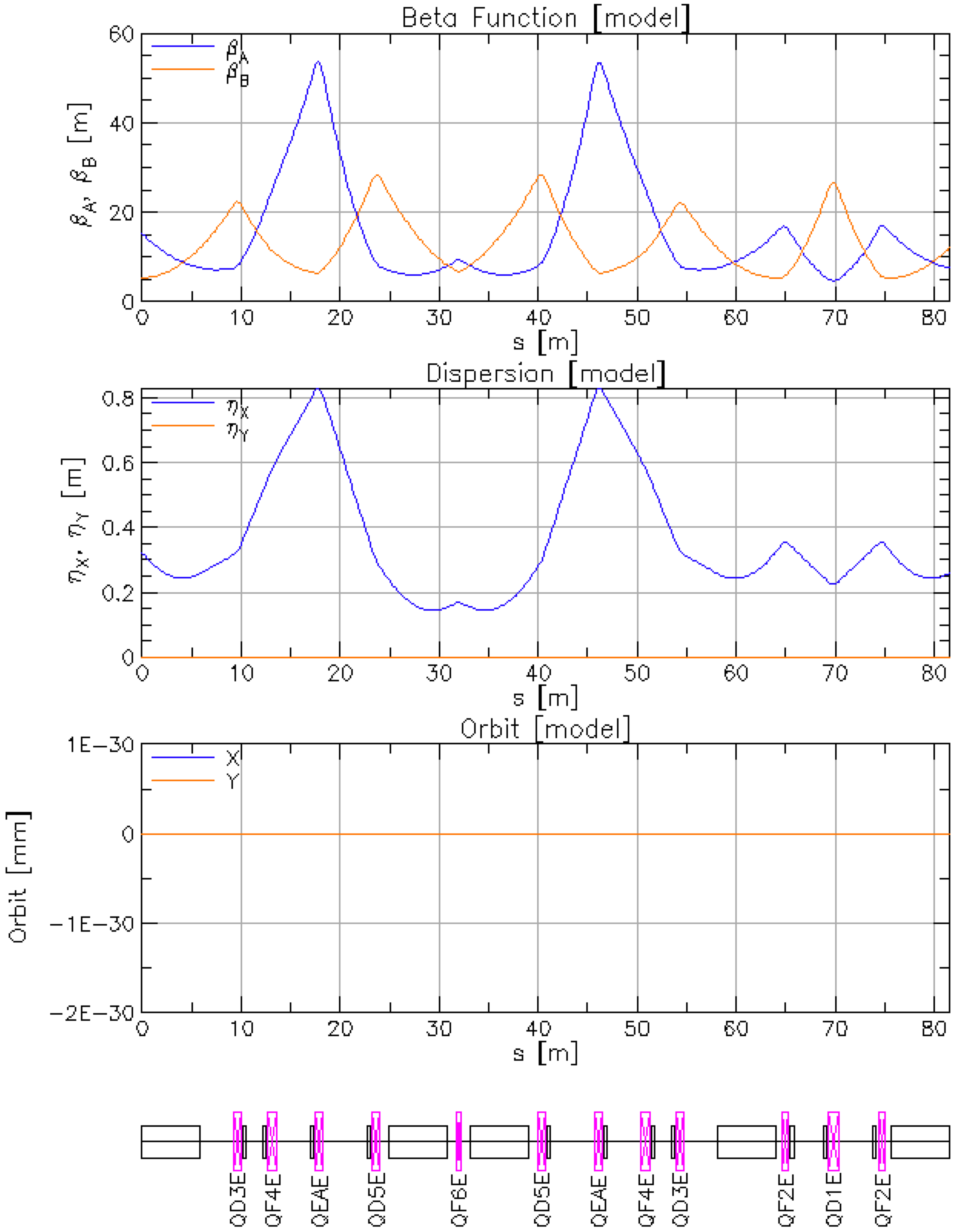
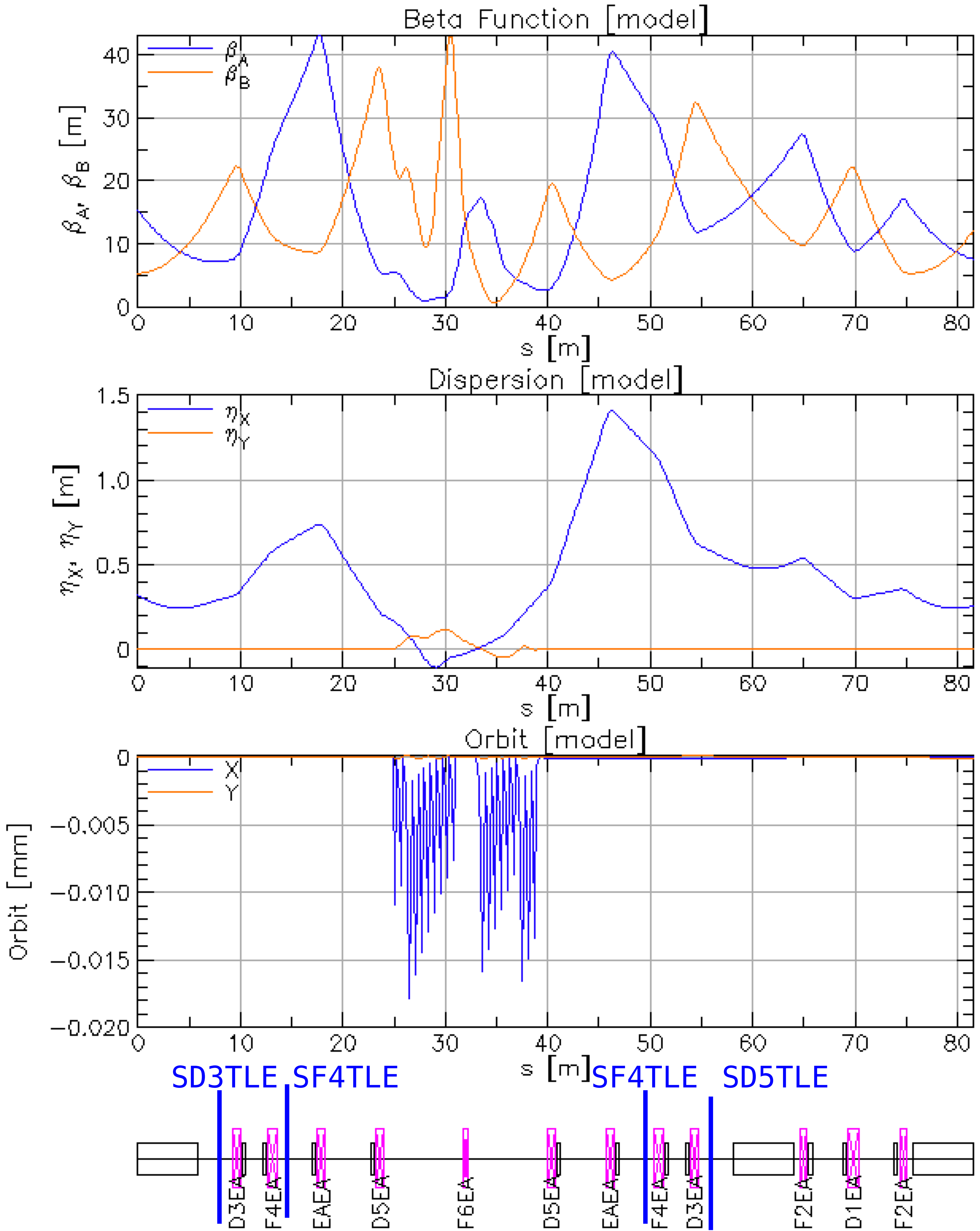
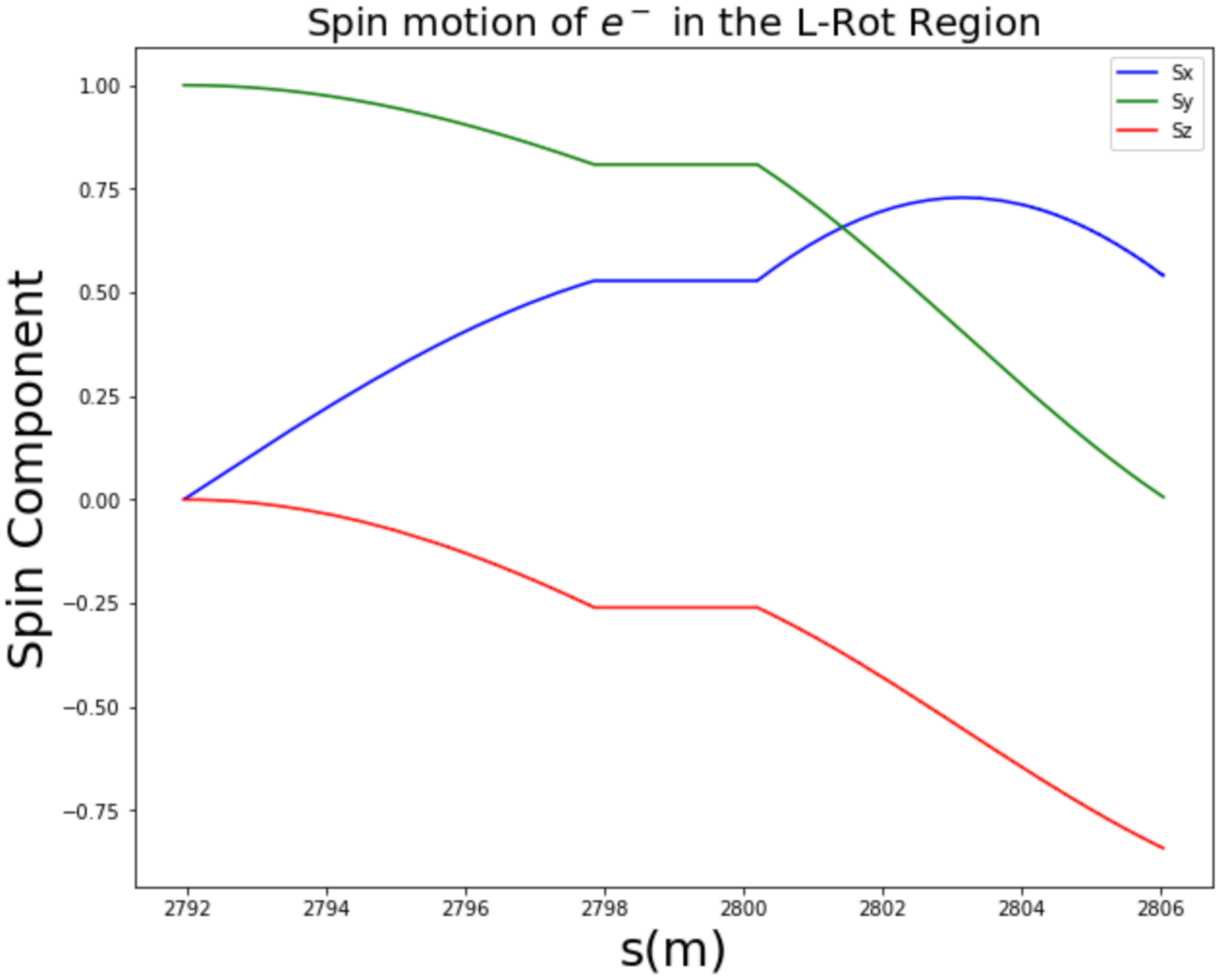
Comparison at L-Rot Region



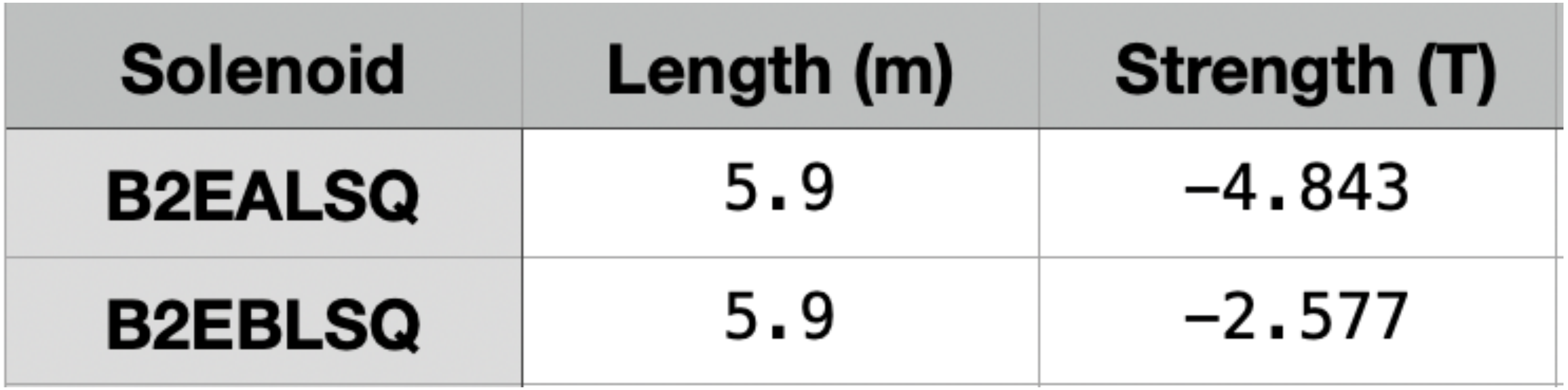
Original



L-Rot

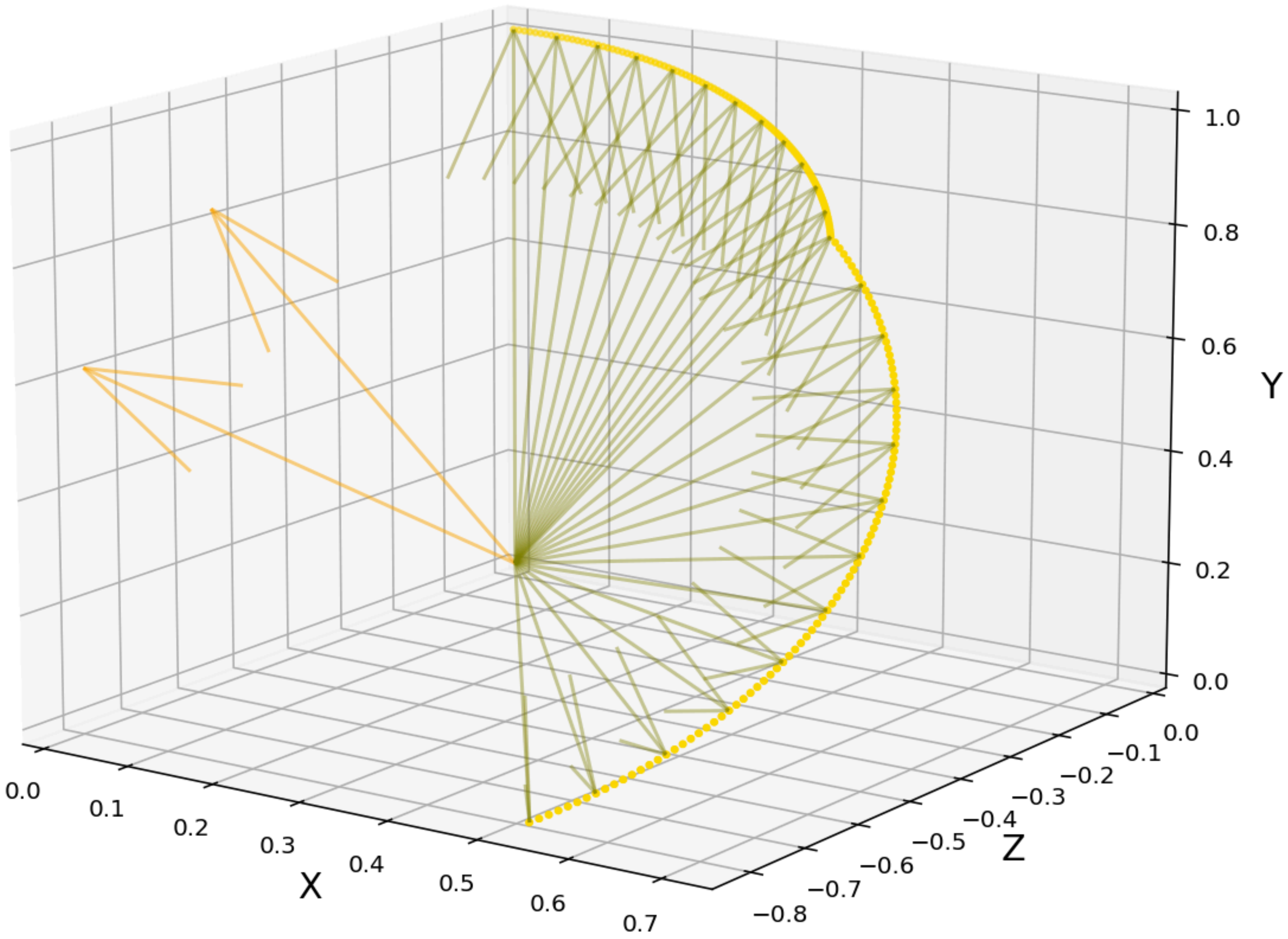

Spin motion of e^- in the L-Rot Region
Sx
Sy
Sz
Spin Component
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
2792
2794
2796
2798
2800
2802
2804
2806
s(m)

L-Rot Solenoid Strength



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

Spin Motion of e^- in the L-Rot Region



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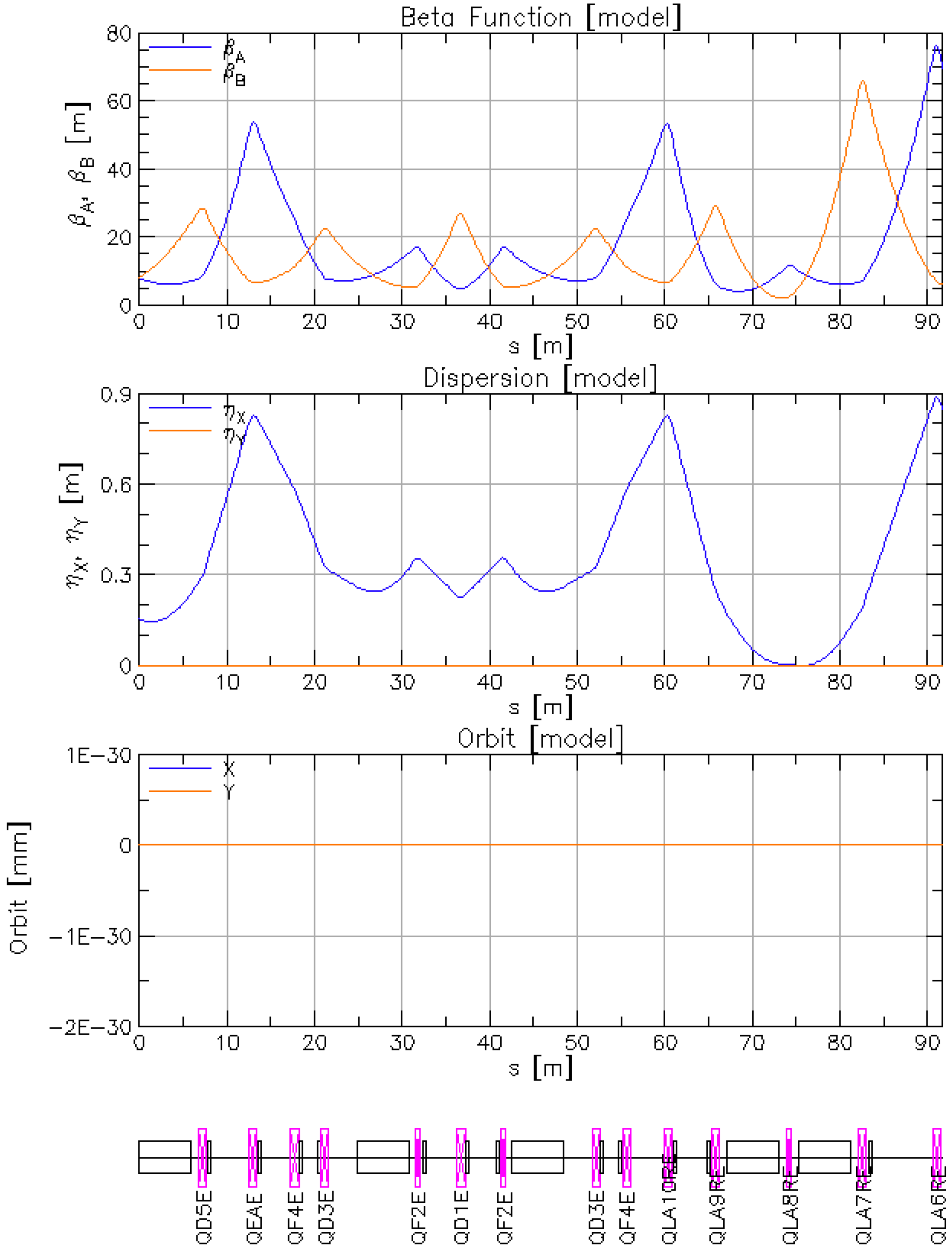
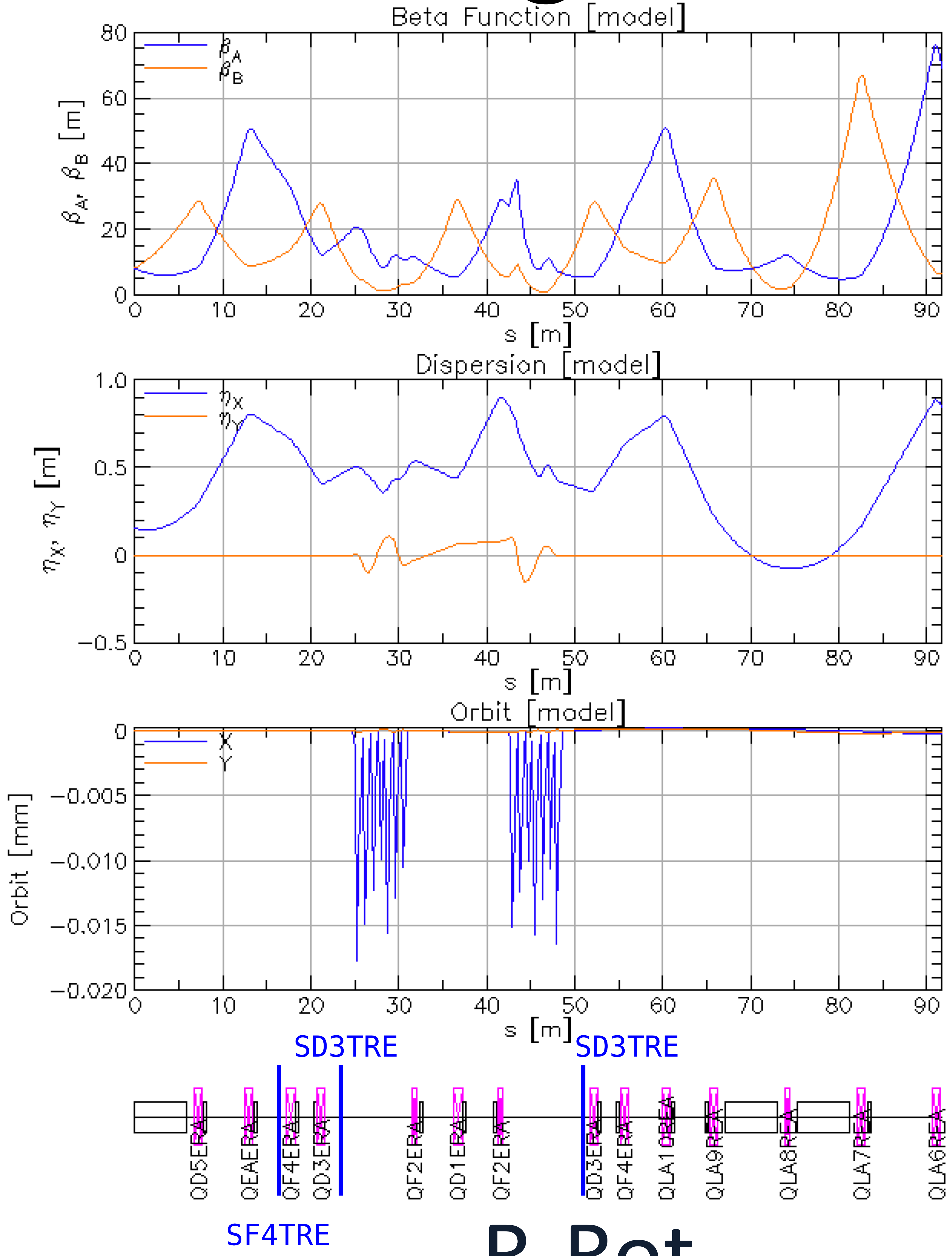
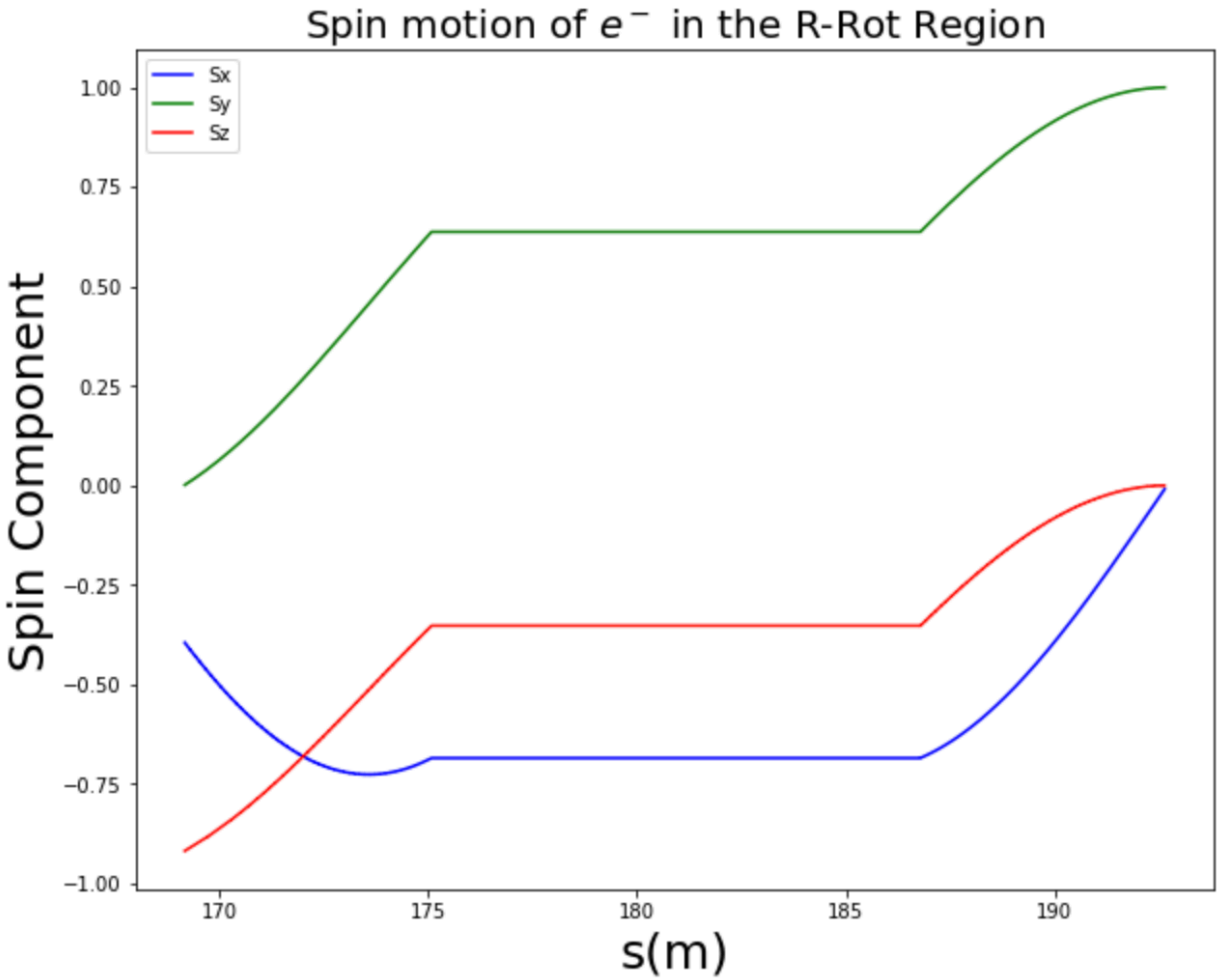
Comparison at R-Rot Region



Original



R-Rot



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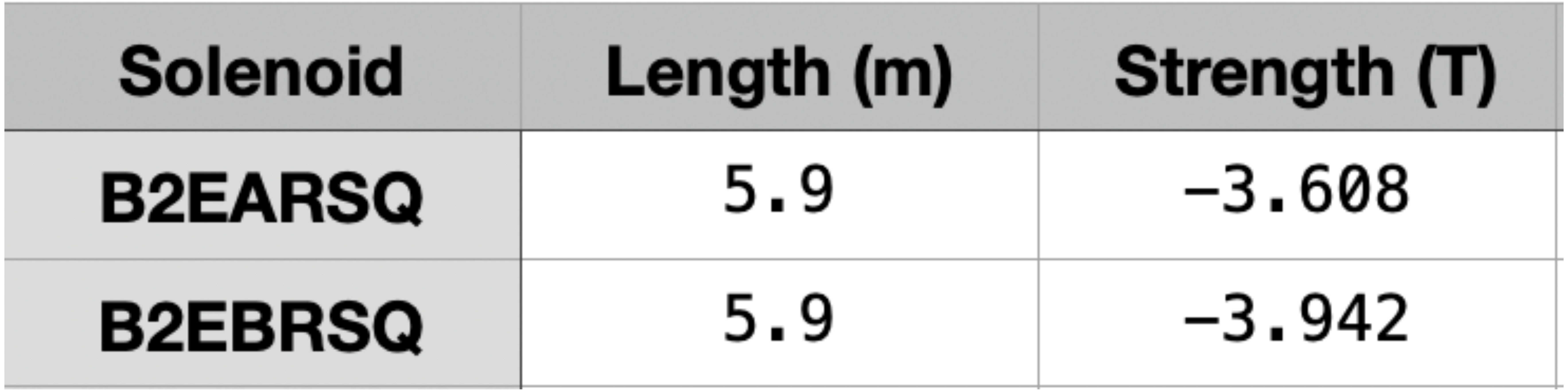
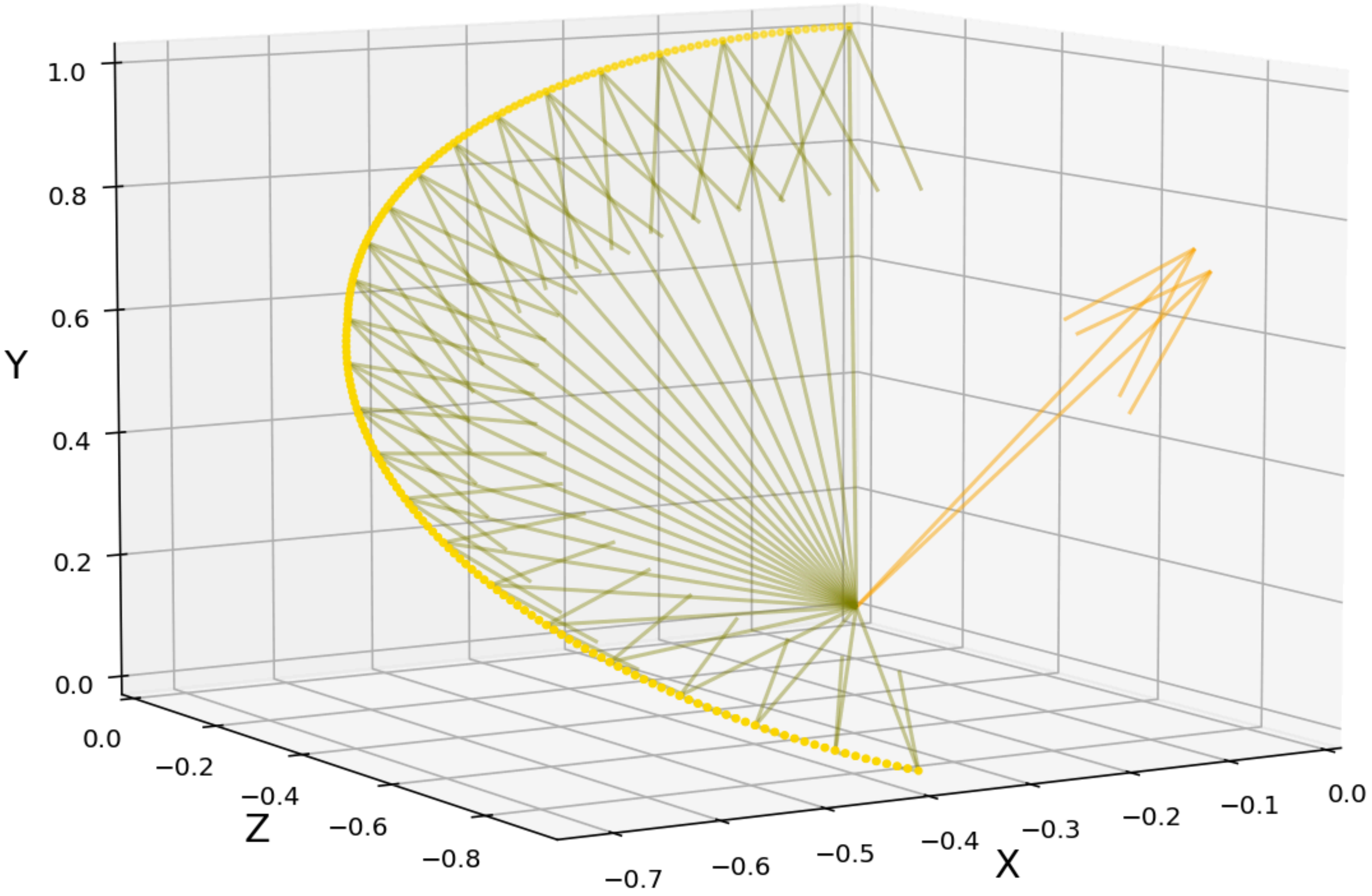
R-Rot Solenoid Strength



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

Spin Motion of e^- in the R-Rot Region



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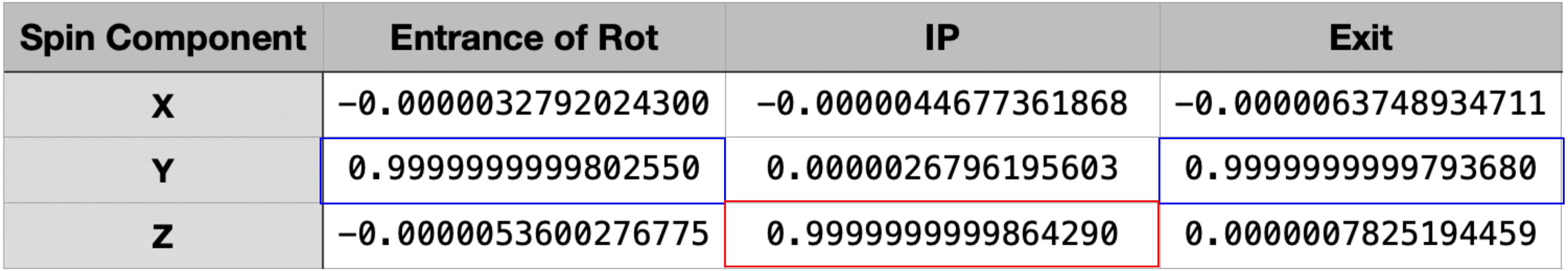
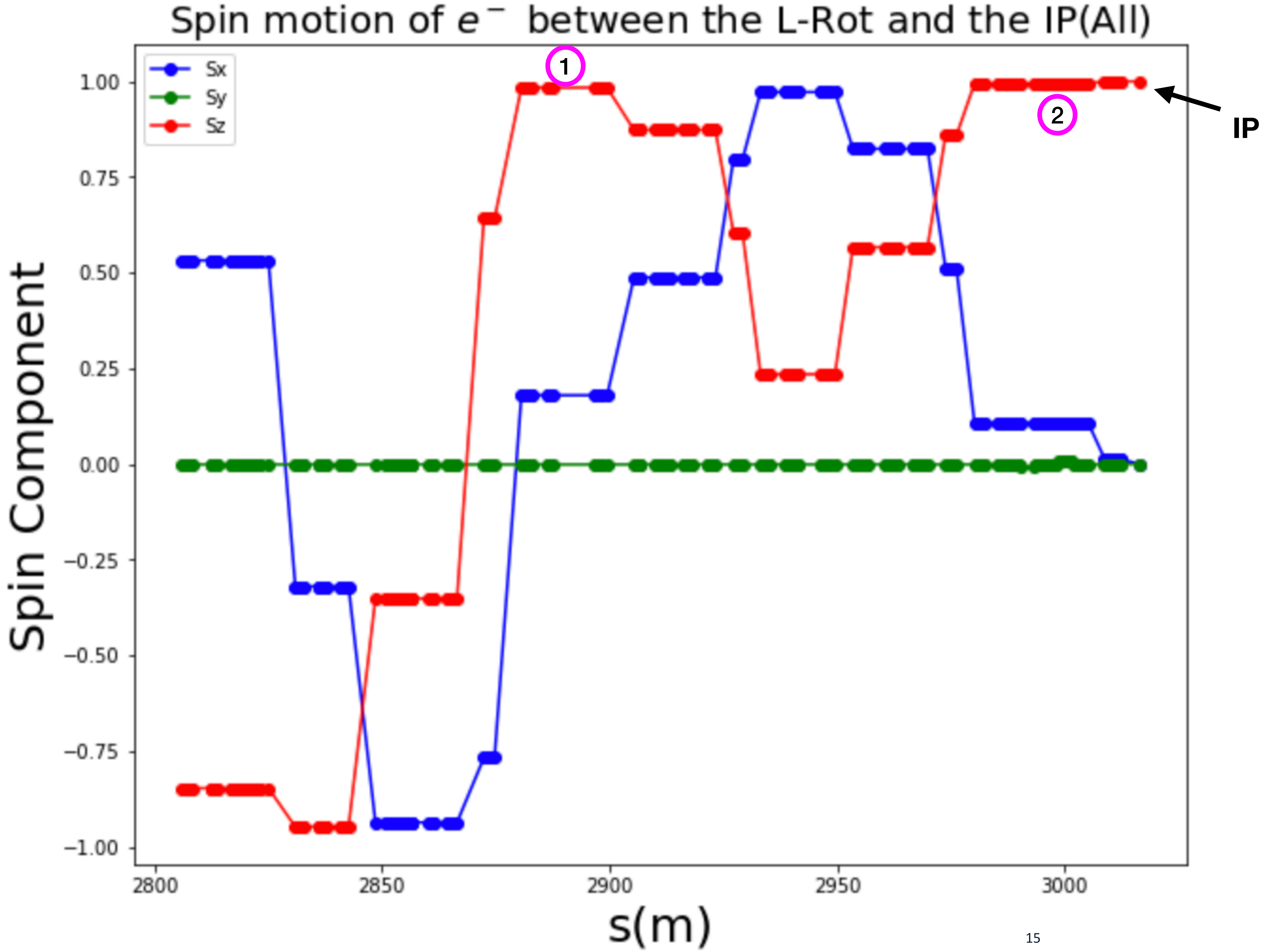
Longitudinal spin alignment at the IP

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

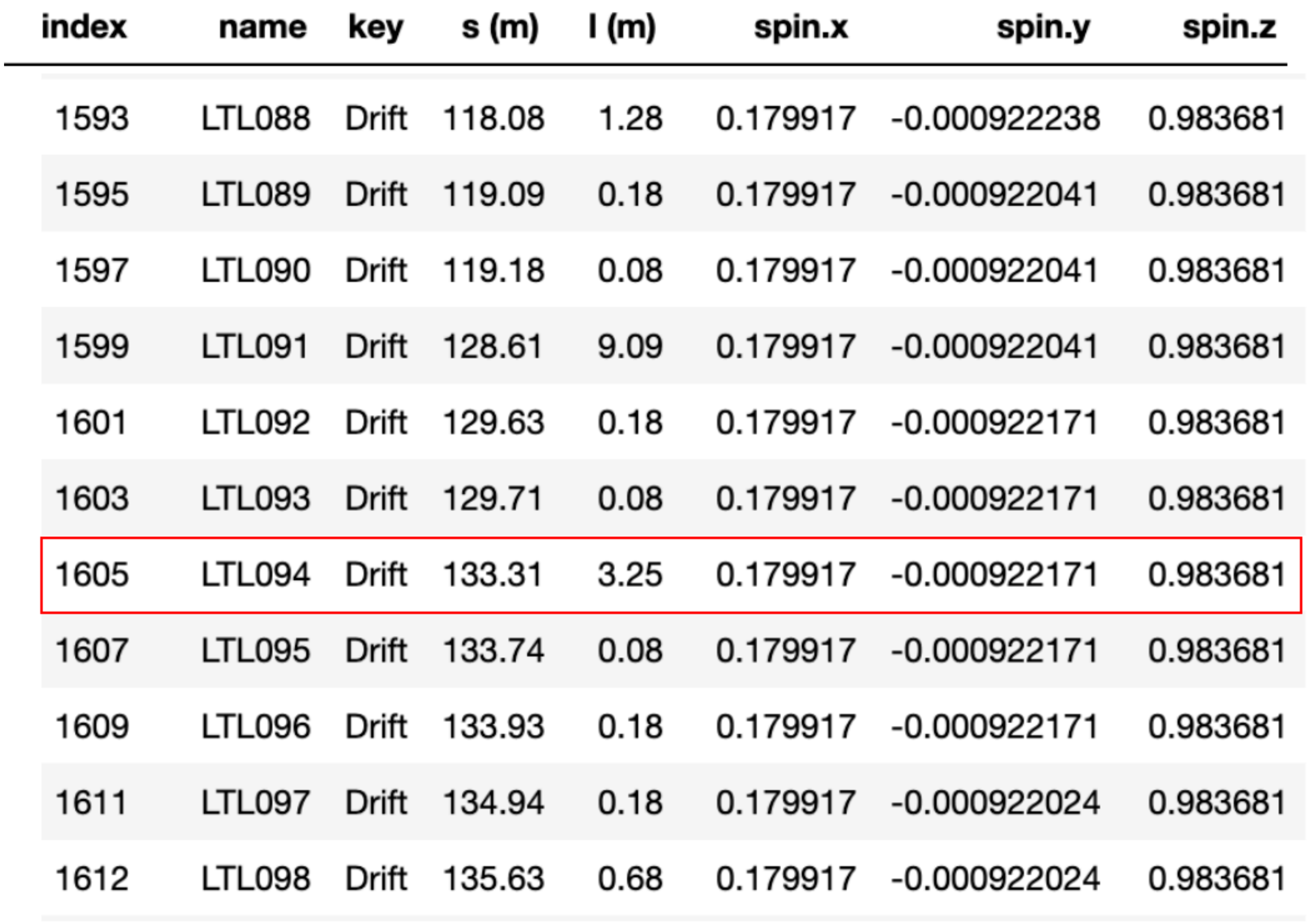


Spin Component	Entrance of Rot	IP	Exit
X	−0.0000032792024300	−0.0000044677361868	−0.0000063748934711
Y	0.9999999999802550	0.0000026796195603	0.9999999999793680
Z	−0.0000053600276775	0.9999999999864290	0.0000007825194459


Spin motion of e^- between the L-Rot and the IP(All)
Sx
Sy
Sz
1
2
IP
Spin Component
s(m)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
2800
2850
2900
2950
3000

At region ①

e^+ ↓



index	name	key	s (m)	l (m)	spin.x	spin.y	spin.z
1593	LTL088	Drift	118.08	1.28	0.179917	-0.000922238	0.983681
1595	LTL089	Drift	119.09	0.18	0.179917	-0.000922041	0.983681
1597	LTL090	Drift	119.18	0.08	0.179917	-0.000922041	0.983681
1599	LTL091	Drift	128.61	9.09	0.179917	-0.000922041	0.983681
1601	LTL092	Drift	129.63	0.18	0.179917	-0.000922171	0.983681
1603	LTL093	Drift	129.71	0.08	0.179917	-0.000922171	0.983681
1605	LTL094	Drift	133.31	3.25	0.179917	-0.000922171	0.983681
1607	LTL095	Drift	133.74	0.08	0.179917	-0.000922171	0.983681
1609	LTL096	Drift	133.93	0.18	0.179917	-0.000922171	0.983681
1611	LTL097	Drift	134.94	0.18	0.179917	-0.000922024	0.983681
1612	LTL098	Drift	135.63	0.68	0.179917	-0.000922024	0.983681

↑ e^-

Notice: the table shows the spin tracking result for the positron

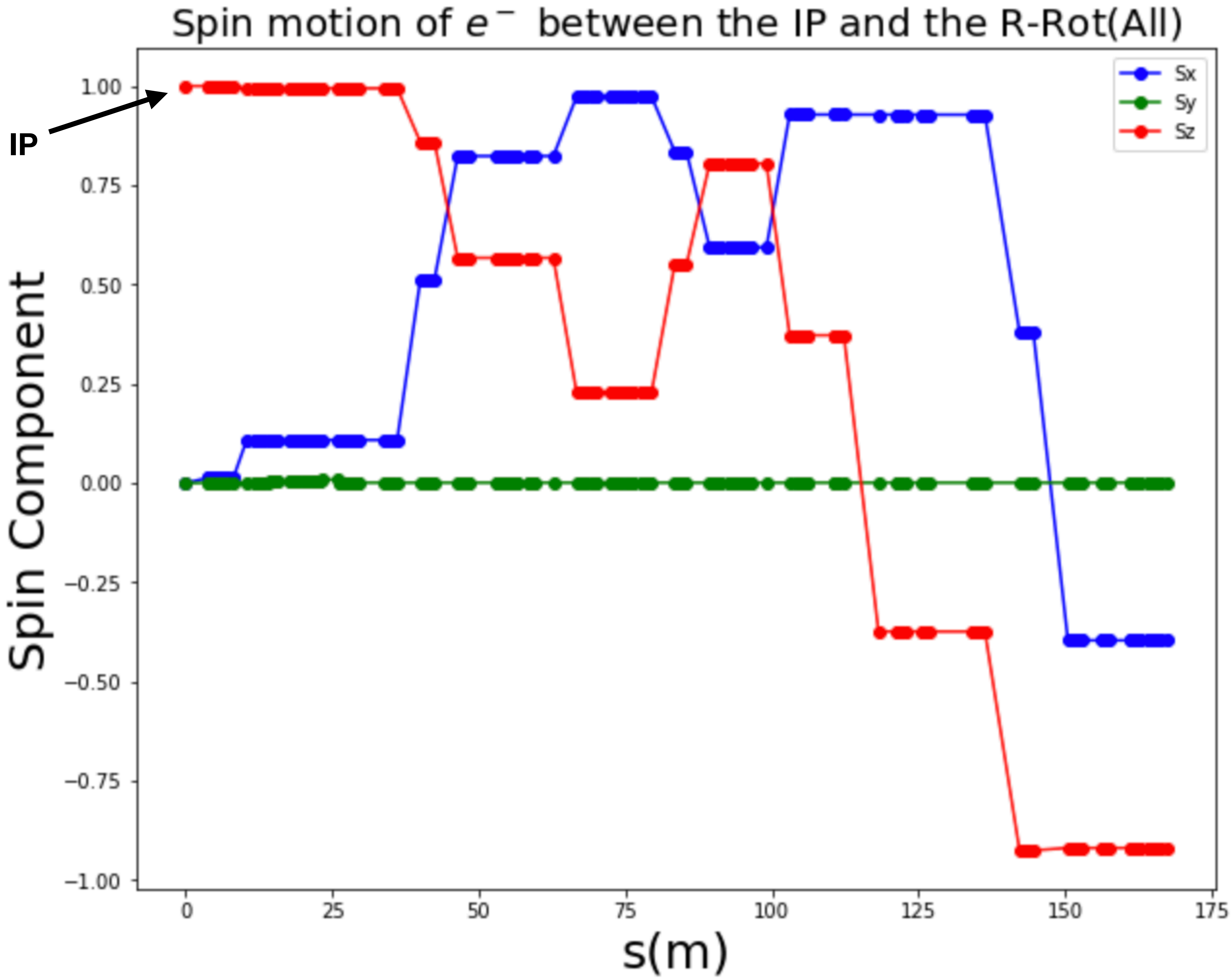
②

e^+ ↓

e^- ↑

index	name	key	s (m)	l (m)	spin.x	spin.y	spin.z
1409	LTL001	Drift	4.1	0.1	0.014015	-0.000921983	0.999901
1411	LTL002	Drift	5.248	0.804	0.014015	-0.000921984	0.999901
1413	LTL003	Drift	5.675	0.083	0.014015	-0.000921984	0.999901
1415	LTL004	Drift	5.856	0.181	0.014015	-0.000921984	0.999901
1417	LTL005	Drift	6.655	0.261	0.0140151	-0.000921989	0.999901
1419	LTL006	Drift	7.504	0.504	0.0140151	-0.000921988	0.999901
1421	LTL007	Drift	11.617	0.51	0.107795	-0.000921988	0.994173
1423	LTL008	Drift	12.2	0.239	0.107795	-0.000921988	0.994173
1425	LTL009	Drift	12.936	0.165	0.107795	-0.000921979	0.994173
1427	LTL010	Drift	14.324	1.388	0.107795	-0.000921979	0.994173
1429	LTL011	Drift	15.047	0.362	0.107795	0.0072246	0.994147
1431	LTL012	Drift	15.547	0.25	0.107795	0.0072246	0.994147
1433	LTL013	Drift	16.826	1.029	0.107795	0.0072246	0.994147
1435	LTL014	Drift	17.693	0.867	0.107795	0.0072246	0.994147
1437	LTL015	Drift	18.291	0.237	0.107795	-0.00184054	0.994171
1439	LTL016	Drift	19.026	0.165	0.107795	-0.00184052	0.994171
1441	LTL017	Drift	19.109	0.083	0.107795	-0.00184052	0.994171
1443	LTL018	Drift	20.197	0.744	0.107795	-0.00184052	0.994171
1445	LTL019	Drift	20.697	0.25	0.107795	-0.00184052	0.994171
1447	LTL020	Drift	21.847	0.9	0.107795	-0.00184052	0.994171
1449	LTL021	Drift	22.012	0.165	0.107795	-0.00184052	0.994171
1451	LTL022	Drift	22.818	0.237	0.107795	-0.00184057	0.994171
1453	LTL023	Drift	25.939	2.76	0.107795	-0.00820915	0.994139
1455	LTL024	Drift	26.537	0.237	0.107795	-0.000922012	0.994173
1457	LTL025	Drift	27.272	0.165	0.107795	-0.00092204	0.994173
1459	LTL026#1	Drift	27.387	0.115	0.107795	-0.00092204	0.994173
1461	LTL026#2	Drift	27.502	0.115	0.107795	-0.00092204	0.994173
1463	LTL027	Drift	28.651	0.549	0.107795	-0.00092204	0.994173
1465	LTL028	Drift	29.282	0.169	0.107795	-0.000922095	0.994173
1467	LTL029	Drift	29.365	0.083	0.107795	-0.000922095	0.994173
1469	LTL030	Drift	30.901	1.192	0.107795	-0.000922095	0.994173
1471	LTL031	Drift	34.011	3.109	0.107795	-0.000922095	0.994173
1473	LTL032	Drift	34.438	0.083	0.107795	-0.000922095	0.994173
1475	LTL033	Drift	34.603	0.165	0.107795	-0.000922095	0.994173
1477	LTL034	Drift	35.338	0.165	0.107795	-0.000922066	0.994173
1478	LTL035	Drift	36.087	0.749	0.107795	-0.000922066	0.994173

Notice: the table shows the spin tracking result for the positron


Spin motion of e^- between the IP and the R-Rot(All)
IP
Sx
Sy
Sz
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
25
50
75
100
125
150
175
Spin Component
s(m)

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 $K_nL \simeq \dfrac{3B_nL}{70}$

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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Spin Dynamics

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

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

The rotation vector is given by :

$$\vec{\Omega} = -\frac{q}{m\gamma}\left((1 + a\gamma)\vec{B}_{\perp} + (1 + a)\vec{B}_{//}\right)$$

$$\vec{\Omega}_{\perp} = -\frac{q}{m\gamma}(1 + a\gamma)\vec{B}_{\perp} \qquad \vec{\Omega}_{//} = -\frac{q}{m\gamma}(1 + a)\vec{B}_{//}$$

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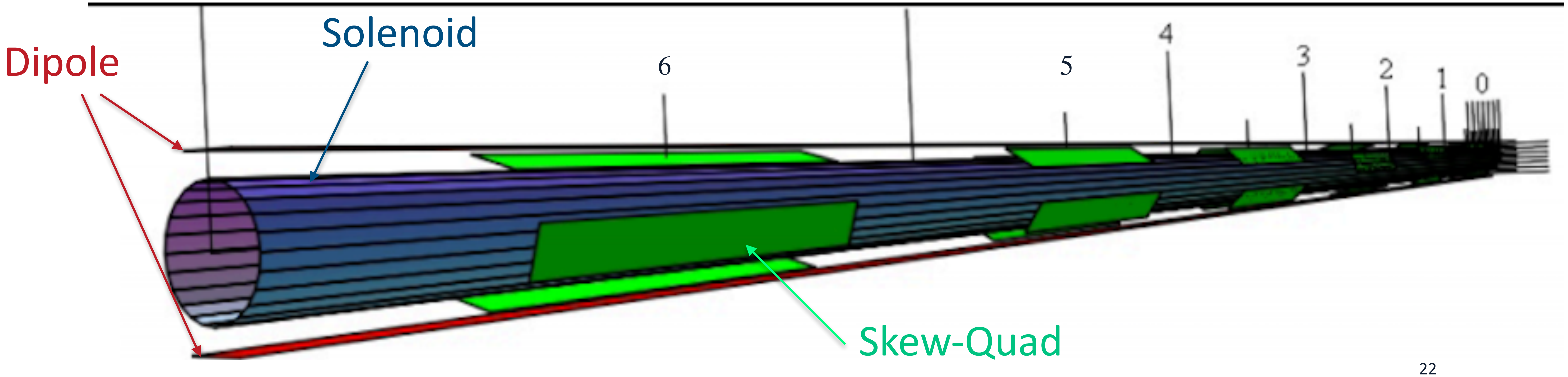
Rotator Magnet Structure

- 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



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

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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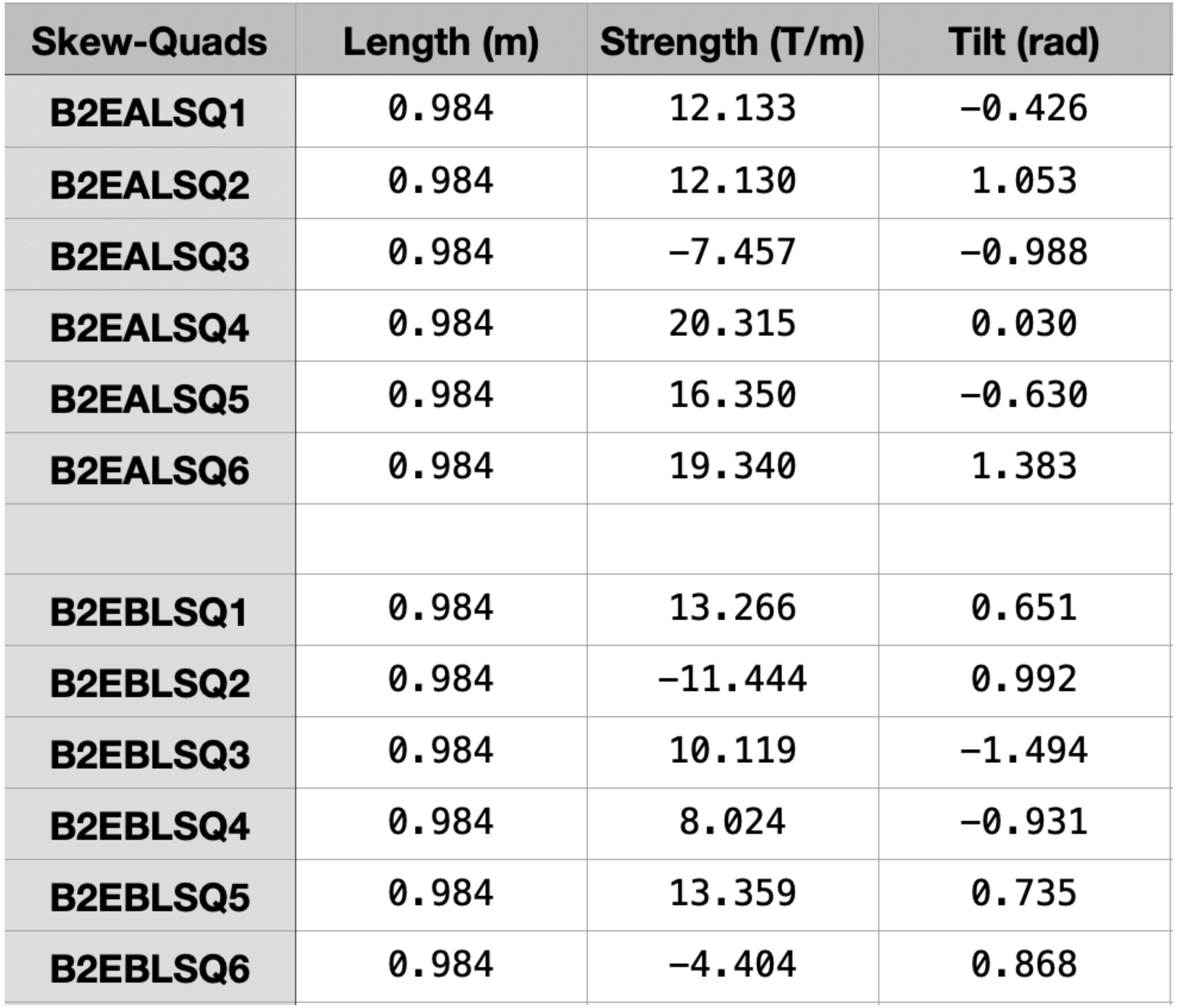
Skew-Quads in the L-Rot



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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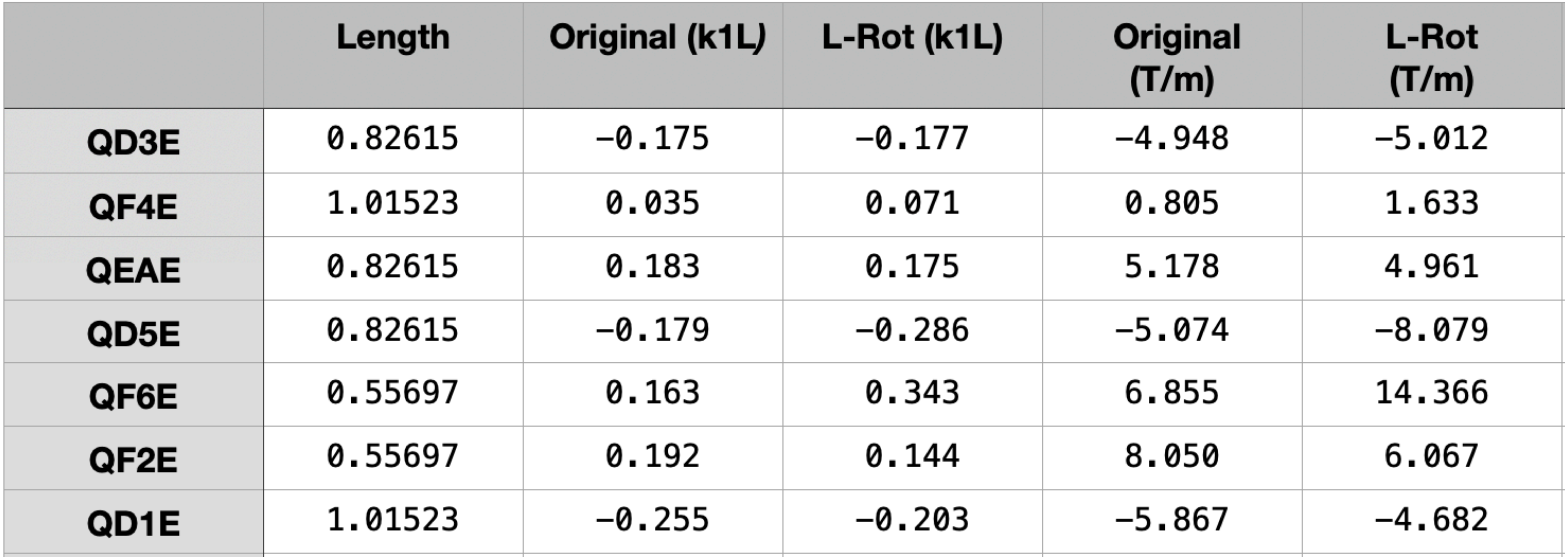
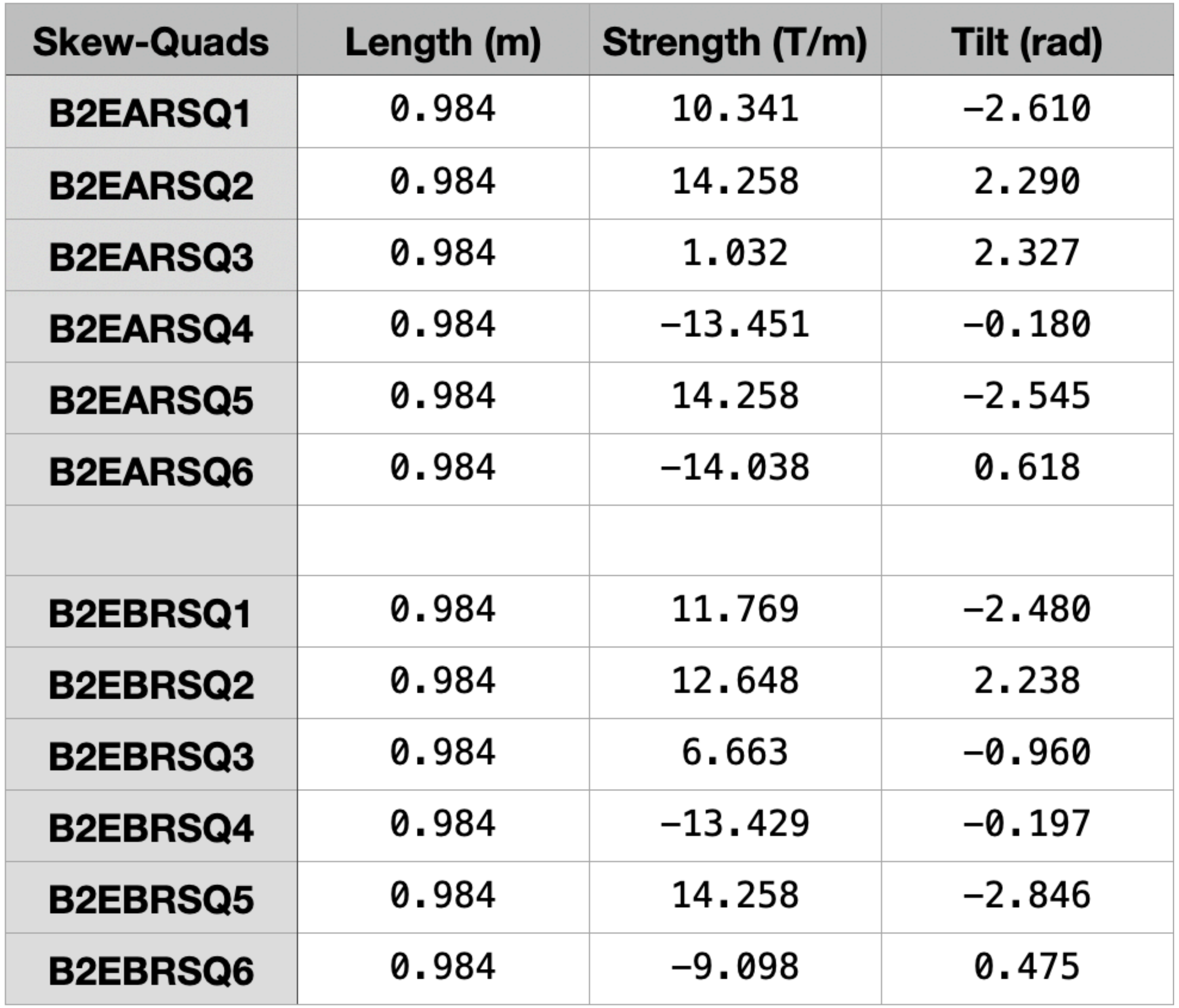
Quads Comparison in the L-Rot Region



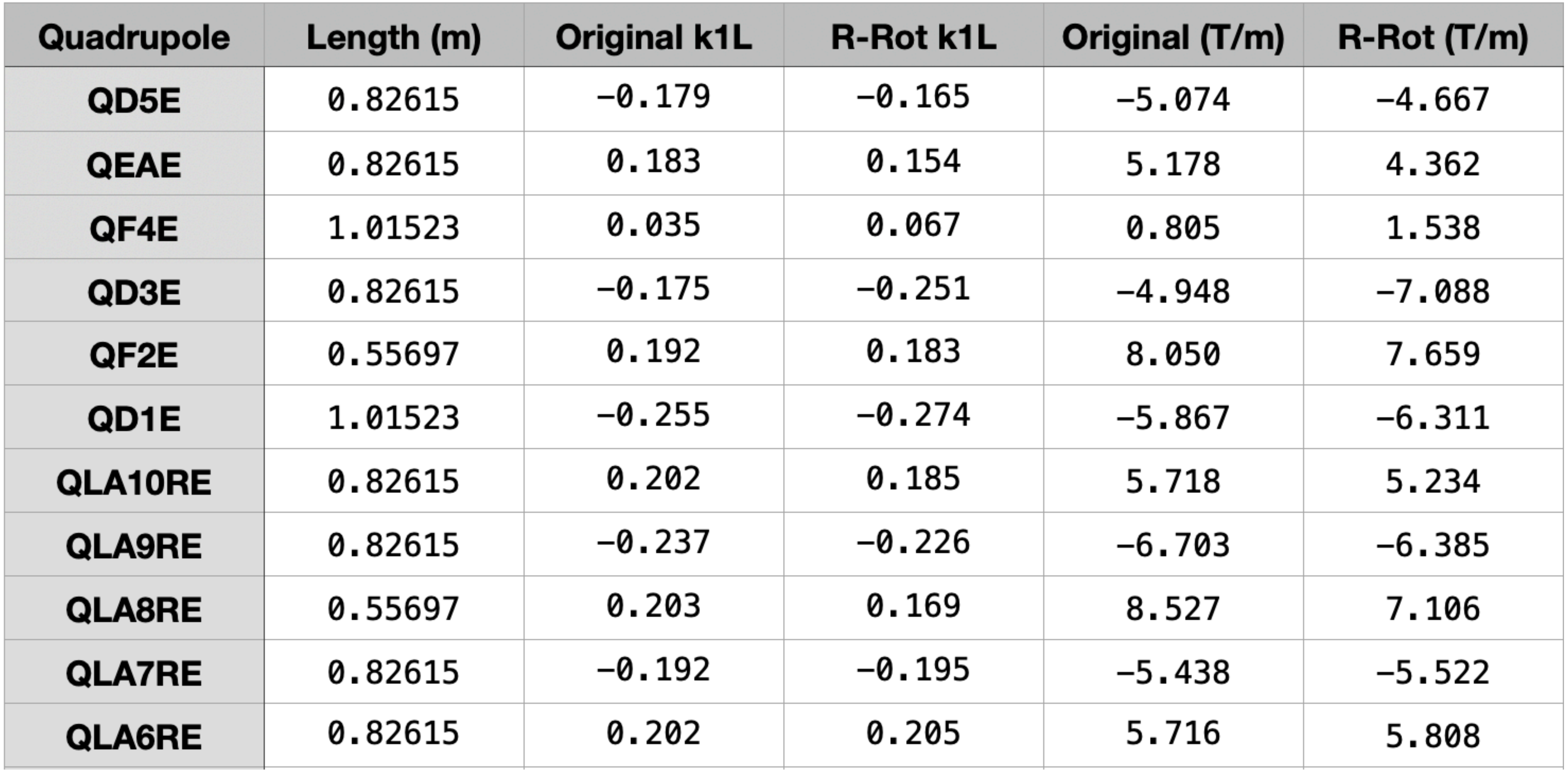
	Length	Original (k1L)	L-Rot (k1L)	Original (T/m)	L-Rot (T/m)
QD3E	0.82615	−0.175	−0.177	−4.948	−5.012
QF4E	1.01523	0.035	0.071	0.805	1.633
QEAE	0.82615	0.183	0.175	5.178	4.961
QD5E	0.82615	−0.179	−0.286	−5.074	−8.079
QF6E	0.55697	0.163	0.343	6.855	14.366
QF2E	0.55697	0.192	0.144	8.050	6.067
QD1E	1.01523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

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

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

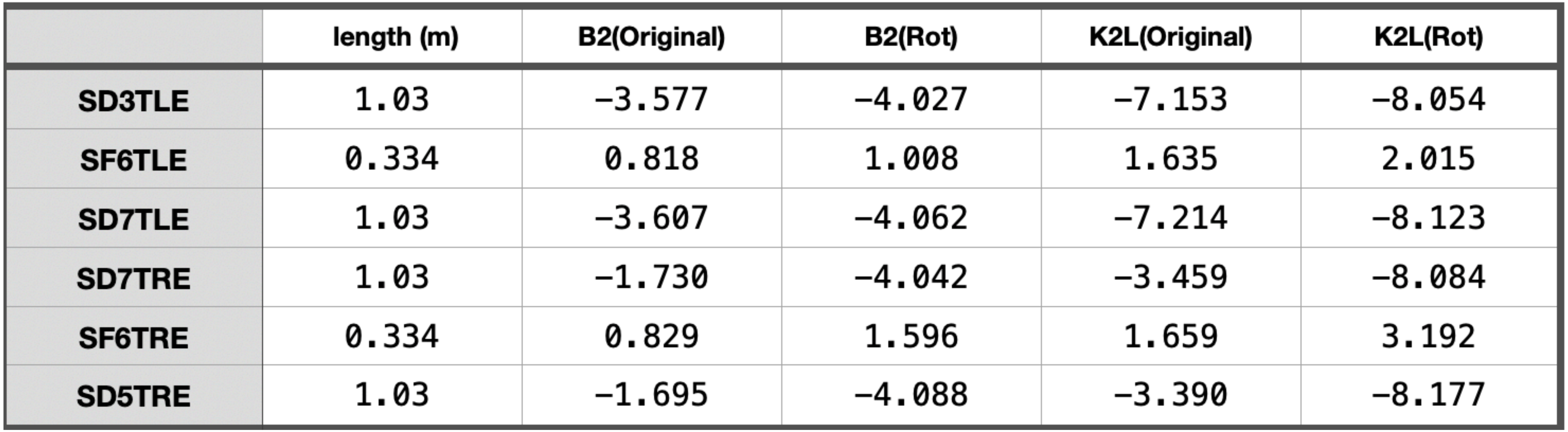
Linear Relationship Between the Chromaticity and the Sextupole Strength

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

- 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

Sextupoles used for fixing the first order chromaticity

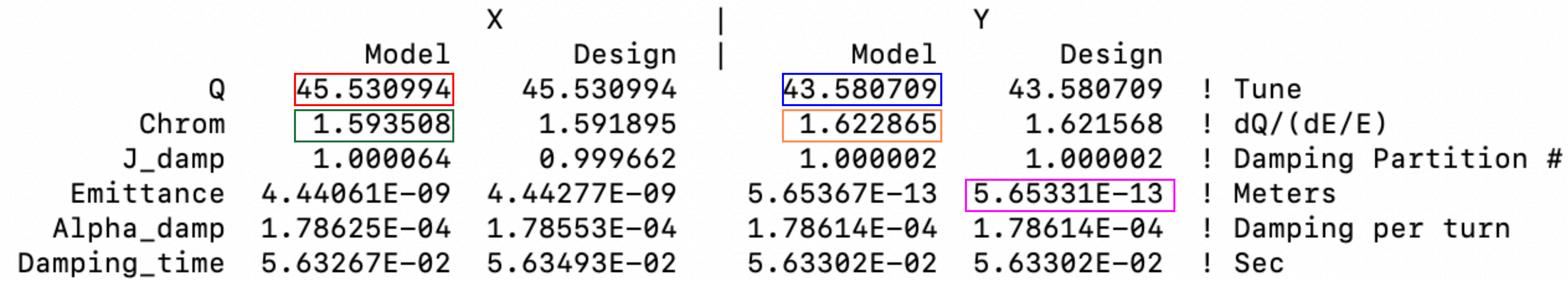
SD5TLE, SF4TLE, and SD3TRE pairs are turned off because the phase difference between these pairs is no longer π



	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

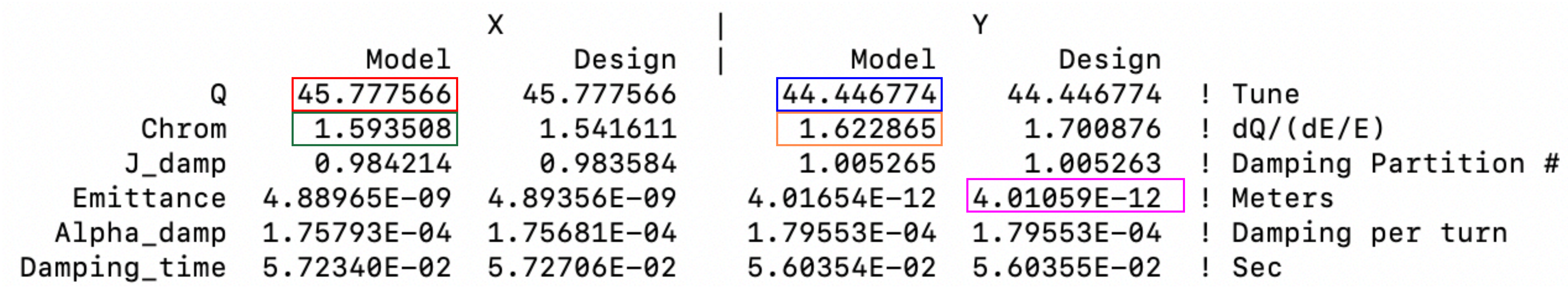
Comparison of Ring Parameters With First Order Chormaticity Fixed

Original



```
                           X                  |                  Y
                     Model         Design     |       Model         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                  |                  Y
                     Model         Design     |       Model         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
```