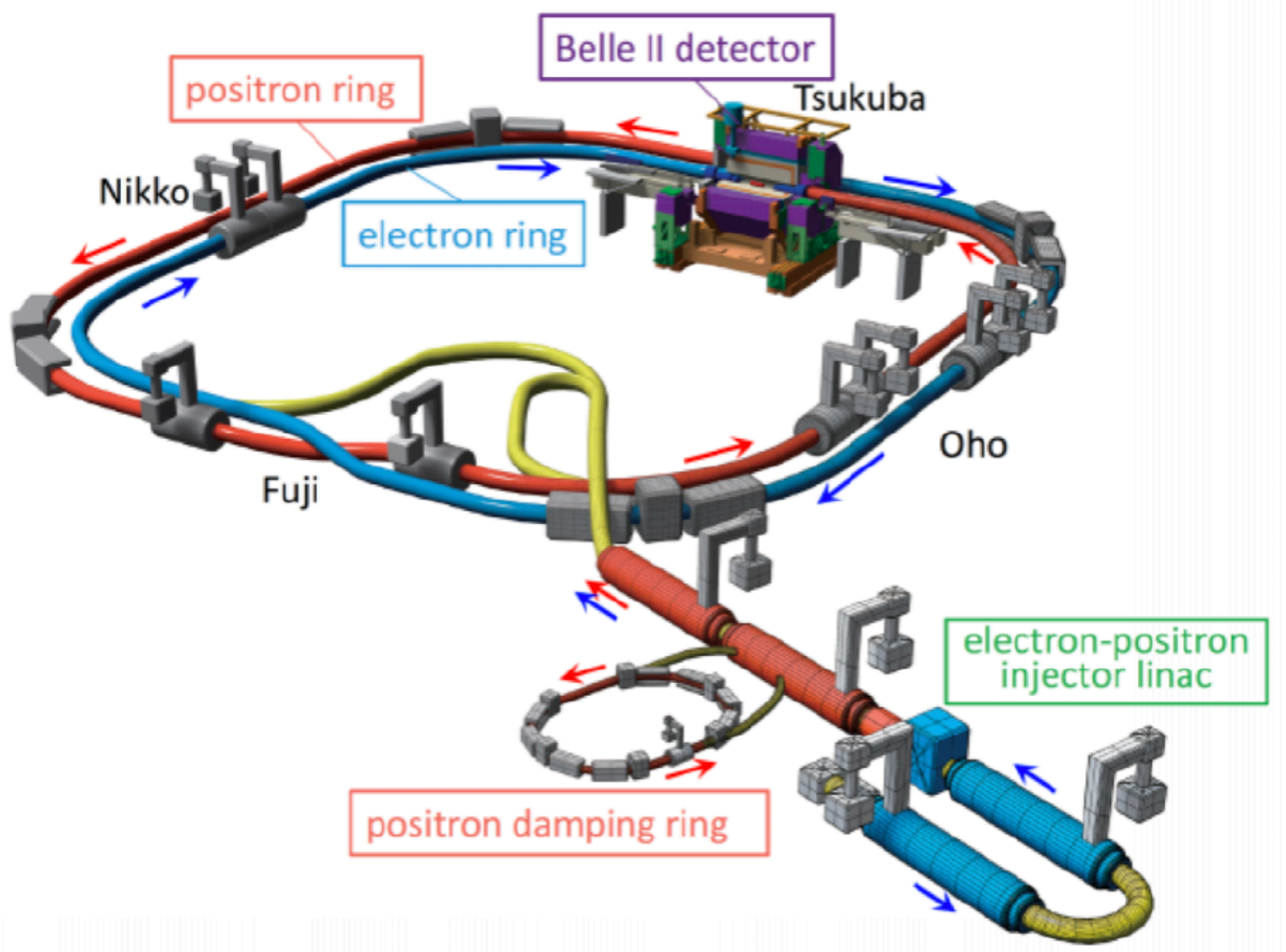
Spin Rotator Design for the SuperKEKB High Energy Ring in a Proposed Polarization Upgrade



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2021.06.22

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Outline

- Overview of this project
- Current Status
- Technical details to be confirmed
- Beam Tracking Progress
- Future Steps

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Purpose

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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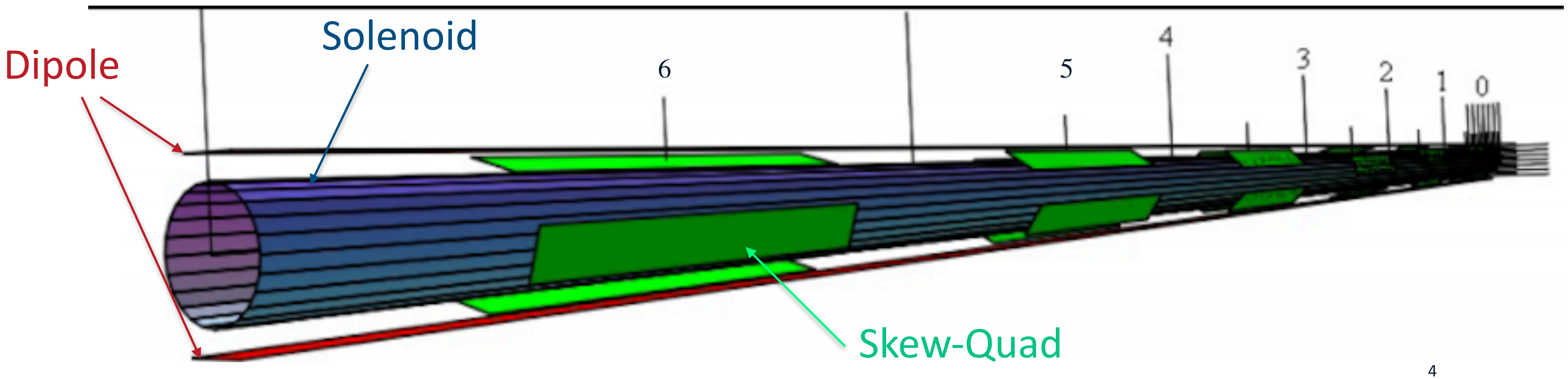
Rotator Magnet

- Follows Uli Wienands's idea and direction:

- replace some existing ring dipoles 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



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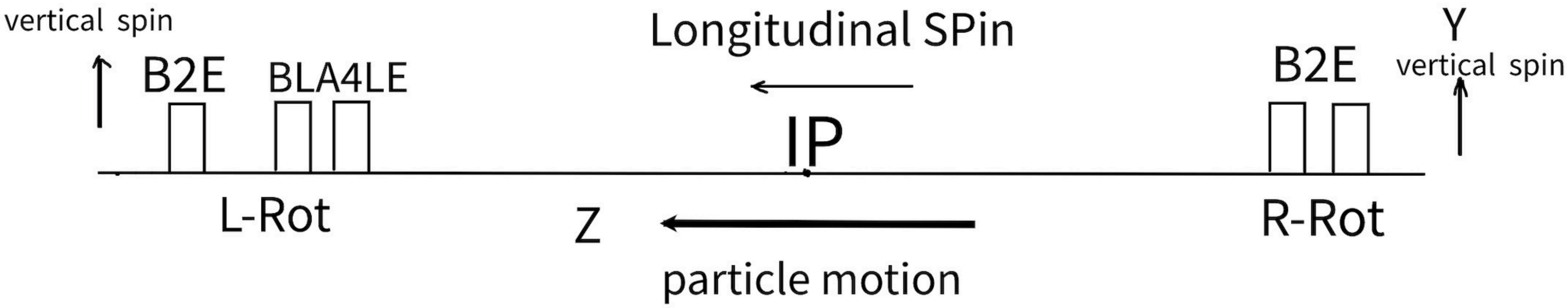
Spin rotator



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

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

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Constraints of the Design

✤**Transparency**:

- Need to maintain the **original optical functions** outside of the rotator region, such as **twiss parameters** (α, β, γ), and **dispersion function**

- Maintain the Beam quality**:** Make the **Emittance** as low as possible

- Maintain the overall machine feature

  - Maintain the original **Chromaticity** $\xi = \dfrac{\Delta Q}{\Delta p/p}$

  - Maintain the original **Tune Value** $Q = \dfrac{\Delta \Psi}{2\pi}$

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

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Procedure of Design and Maintaining Transparency

- 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
  - Tune the chromaticity with ring sextupoles
  - Maintain the Tune value Q

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Main Difficulties

- To make the vertical emittance as small as possible, need to add extra constraints on the vertical dispersion function when performing the decoupling with skew-quads, which requires strong skew-quads

- The stronger skew-quads are, the more they change the optical functions, which needs strong ring quads to do the optical rematch

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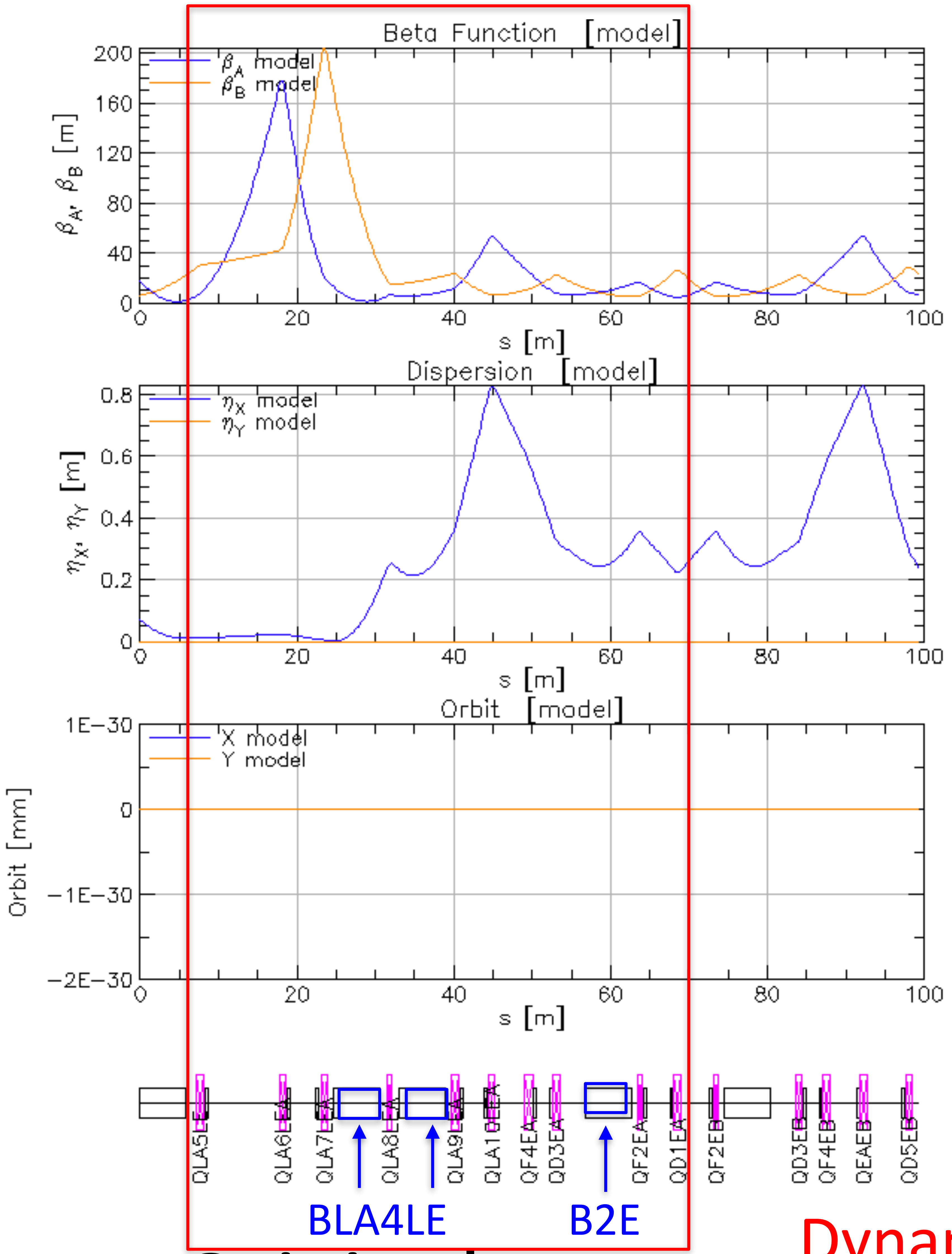
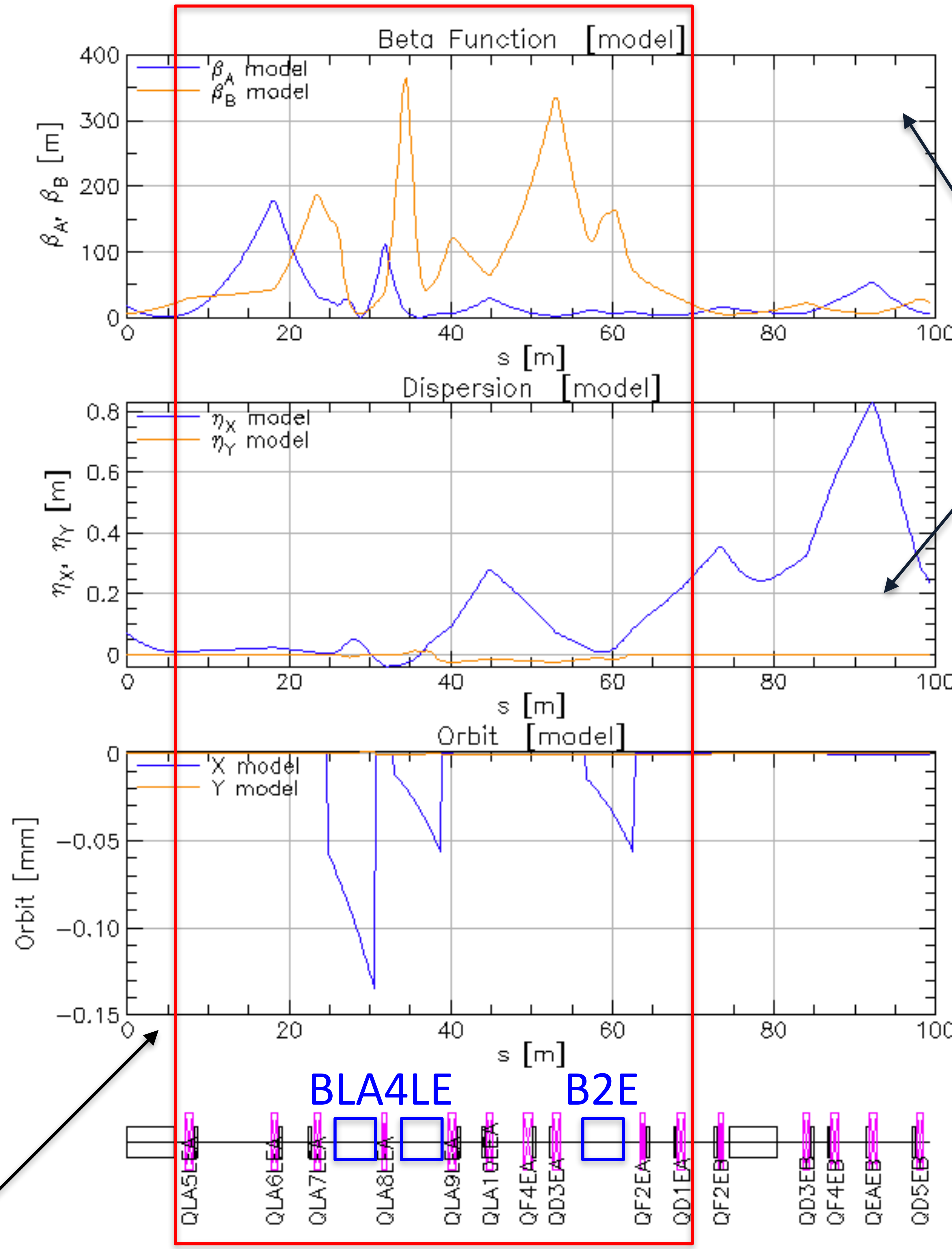
Lattice Comparison at L-Rot Tuning Region



Original



L-Rot

Outside the red box, dynamics maintained as the original after rematching

Dynamics changed in the rotator region

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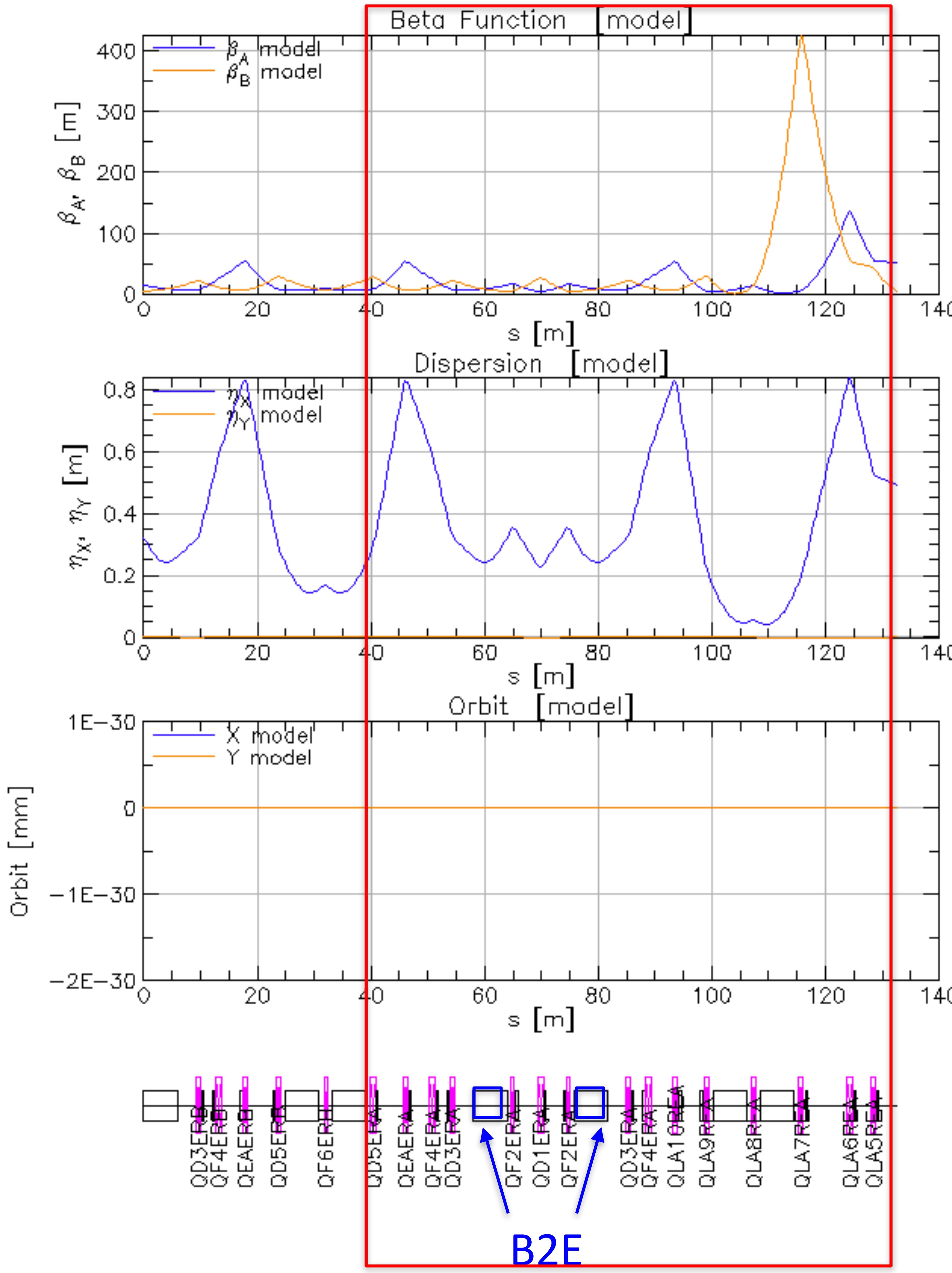
Lattice Comparison at R-Rot Tuning Region



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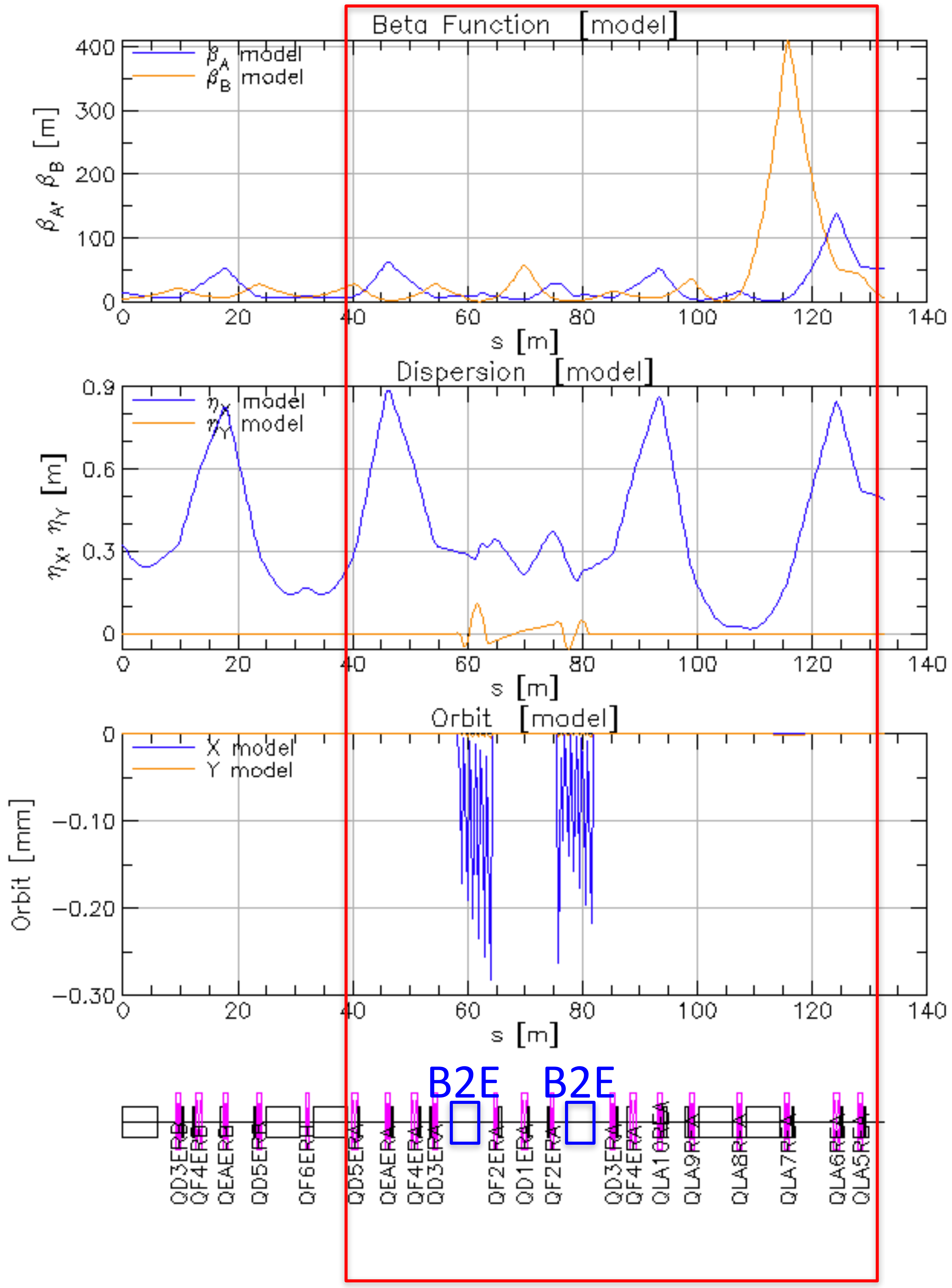

R-Rot

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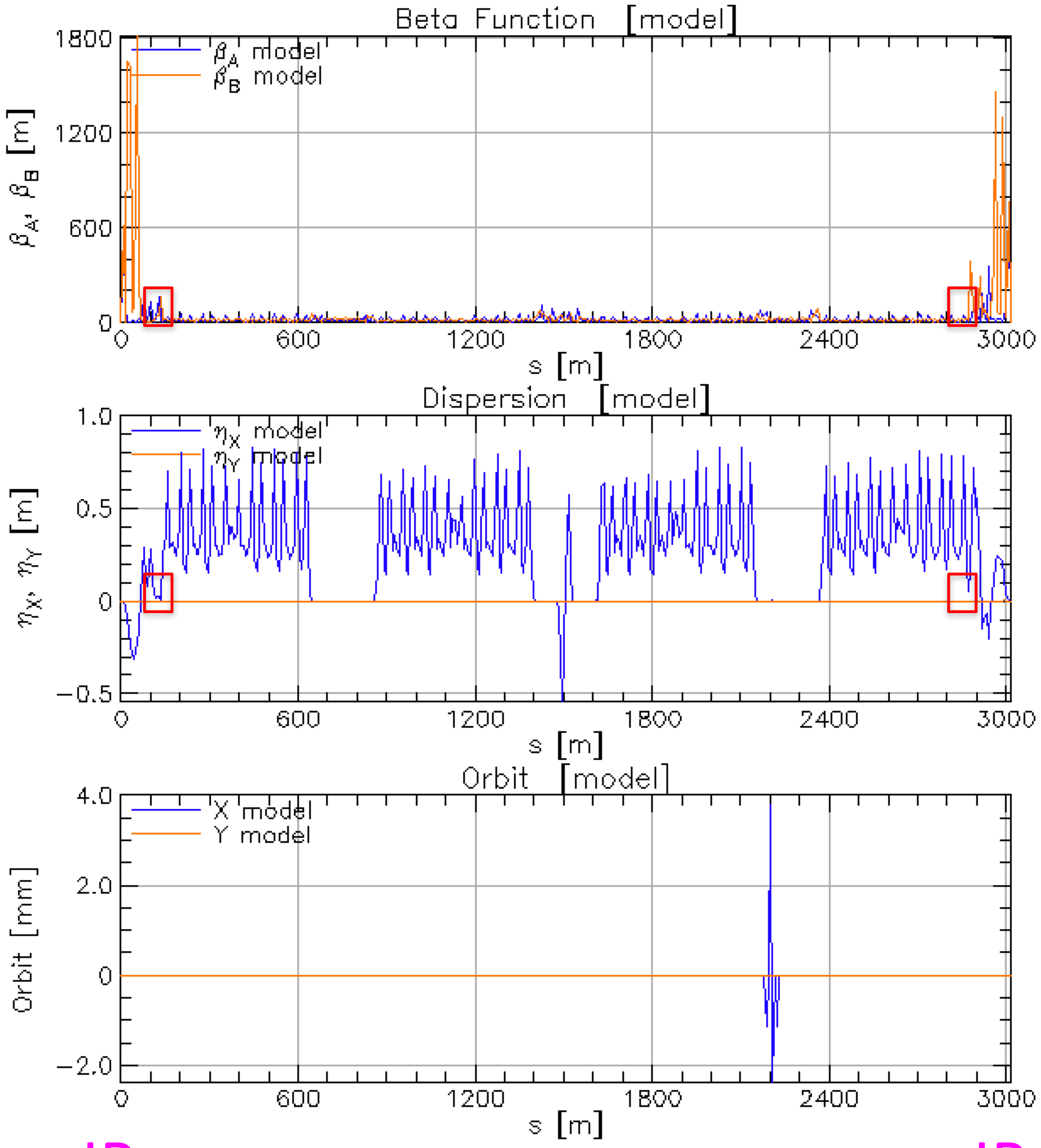
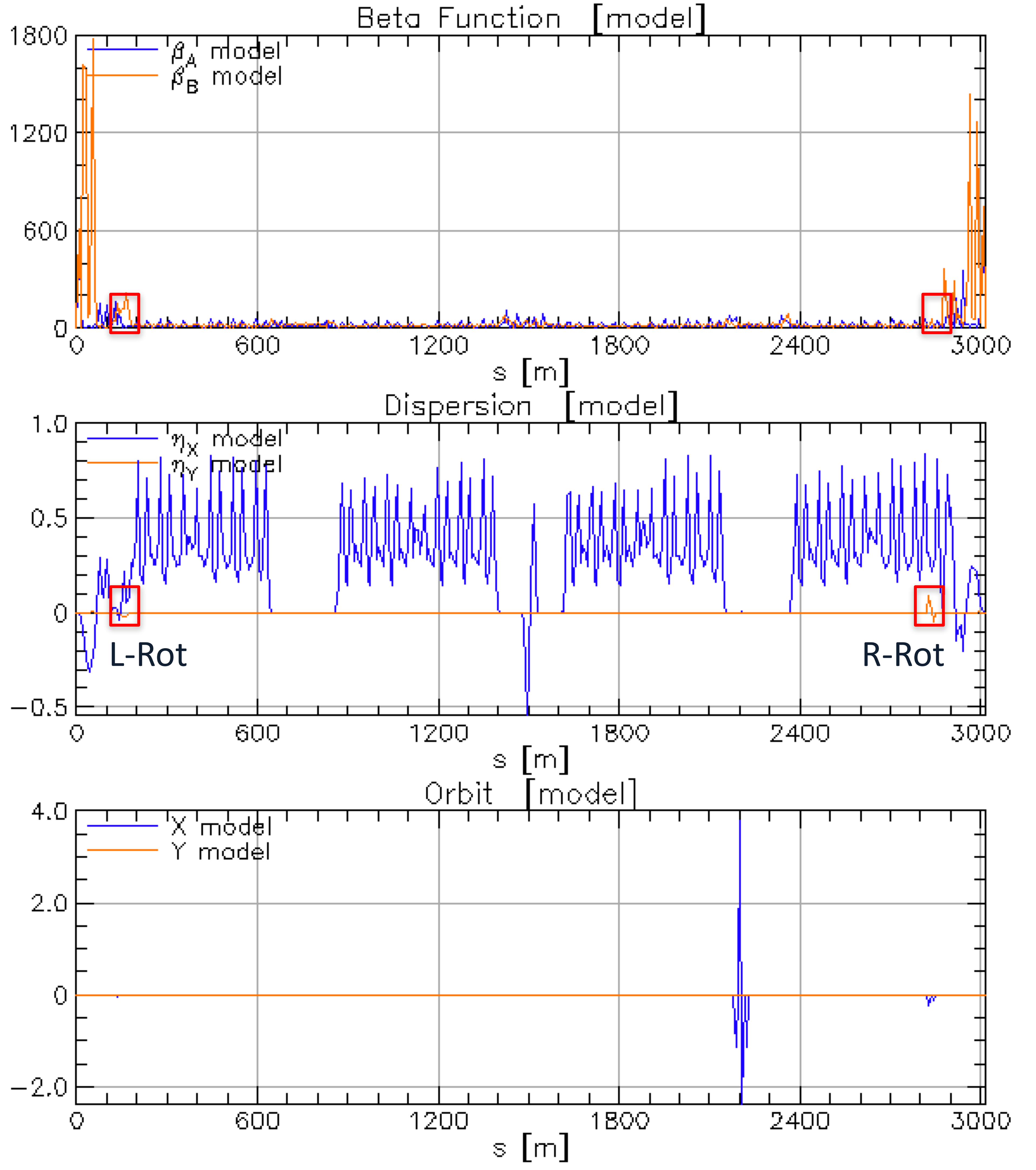
Comparison of full-lattice



IP IP

Original



Rotator Installed

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Longitudinal spin alignment

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

Spin Component	Spin at the entrance of the Rotator	Spin at the IP	Spin at the exit of the Rotator
X	0.00139185	0.00094458	−0.00284127
Y	**0.99999508**	−0.00115044	**0.99999508**
Z	0.00281270	**0.99999889**	−0.00133075

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Chromaticity

$$\xi_{tot} = \frac{1}{4\pi} \oint \Big[m(s)D(s) + k(s) \Big] \beta(s) ds$$

- Where m is the strength of the sextupole; D is the dispersion function; k is the quadrupole strength; β is the beta function

- There exists a linear relationship between the chromaticity and the sextupole strength, and the slope is proportional to the product of D and β

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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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Comparison of the Ring Property After Chrom Tuning

Original

	X Model	X Design	Y Model	Y Design	
Q	45.529986	45.529986	43.569032	43.569032	! Tune
Chrom	3.953515	3.953515	6.595477	6.595477	! dQ/(dE/E)
J_damp	1.000065	0.999667	1.001851	1.001851	! Damping Partition #
Emittance	4.43516E-09	4.43705E-09	1.87884E-12	1.87783E-12	! Meters

Spin Tune: 9.77416E-02 9.77416E-02 ! Spin Tune on Closed Orbit (Units of 2pi)

Rotator Installed

	X Model	X Design	Y Model	Y Design	
Q	46.424717	46.424717	43.919945	43.919945	! Tune
Chrom	3.953515	3.953515	6.595477	6.595477	! dQ/(dE/E)
J_damp	1.247909	1.243933	1.006355	1.006161	! Damping Partition #
Emittance	3.57009E-09	3.57935E-09	7.74755E-12	7.68478E-12	! Meters

Spin Tune: -1.84712E-01 -1.84712E-01 ! Spin Tune on Closed Orbit (Units of 2pi)

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Quadrupole Strength Comparison

Quadrupole	Length (m)	Original (T/m)	L-Rot (T/m)	Original k1L (1/m)	L-Rot k1L (1/m)
qla6le	0.826	5.881	5.401	0.208	0.191
qla7le	0.826	−5.601	−5.221	−0.198	−0.184
qla8le	0.570	**13.941**	**26.613**	**0.340**	**0.649**
qla9le	0.826	−4.315	−6.600	−0.153	−0.233
qla10le	0.826	5.414	6.784	0.1913	0.24
qf4e	1.015	0.805	0.309	0.0349	0.013
qd3e	0.826	−4.948	−5.244	−0.175	−0.185
qf2e	0.557	8.050	1.456	0.192	0.035
qd1e	1.015	−5.868	−0.764	−0.255	−0.033

- If new Qla8le is too strong?
- Can it be built and installed?

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Answer to the Questions

Thanks Mika Masuzawa for answering these questions:

- the current limit of QLA8LE is ~17T/m, K1~0.4 with a new power supply of 700A max

- If we use q quadrupole of different type and run it with higher currents (meaning, need a new power supply of 1000A class), K1 ~ 0.6 is possible

- For now we assume new magnet for QLA8LE

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Sextupole Strength

	length (m)	b2(Original)	K2L(Original)	b2 (0%Sx 1.7%Sy)	K2L (0%Sx 1.7%Sy)
SD5TLE	1.03	-0.4056	-0.8112	-4.075	-8.150
SF6TLE	0.334	0.181	0.362	1.936	3.873
SD7TLE	1.03	-3.473	-6.945	-4.073	-8.147
SD7TRE	1.03	-4.767	-9.533	-4.072	-8.145
SD5TRE	1.03	-2.095	-4.191	-4.070	-8.141

- In order to tune the first order chromaticity, strength of Sly magnets is increased by 1.7%

- Are SLy sextupoles touchable at 1.7% level?

- Are these SD sextupoles the same type of magnet?

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Long_Term_Tracking

PTC: tracking element by element (slow)

Map: Taylor series (fast)

Map does work well when spin tracking, radiation damping, and stochastic effect are turned on (David Sagan mentioned it), so we are using PTC

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Long_Term_Tracking Progress

- Bunch centre at 0 and setting the energy spread to be 6.3E-4
- Tracking 100 particles by running 2000 turns (20ms in lab frame), all particle are alive in the original lattice (sher5780); lost 2 particles in the rotator lattice (Bunch repetition rate is 50 Hz)
- The spin polarization is well preserved in 2000 turns

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Future Steps

- Continue multi-turn beam tracking studies with BMAD to see the beam lifetime(explore turning Touschek on)
- Maintain the Tune value Q and tune the spin tune
- Calculate the longitudinal spin polarization lifetime

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Appendix

The normalized integrated multipole $K_n L$ can be used when specifying magnetic multipole components

$$K_n L \equiv \frac{qB_n L}{P_0}$$

- 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, $K_n L$ can be approximately calculated by $K_n L \simeq \dfrac{3B_n L}{70}$

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Quadrupole	Length (m)	Original (T/m)	R-rot (T/m)	Original K1L (1/m)	R-rot K1L (1/m)
qd5e	0.826	−5.074	−6.079	−0.179	−0.215
qeae	0.826	5.178	5.490	0.183	0.194
qf4e	1.015	0.805	0.627	0.0349	0.027
qd3e	0.826	−4.948	−6.475	−0.175	−0.229
qf2e	0.557	8.050	6.497	0.192	0.155
qd1e	1.015	−5.867	−6.679	−0.255	−0.29
qla10re	0.826	5.848	6.142	0.207	0.217
qla9re	0.826	−8.794	−8.557	−0.311	−0.302
qla8re	0.557	11.457	12.264	0.273	0.292
qla7re	0.826	−5.078	−5.125	−0.179	−0.181
qla6re	0.826	5.319	5.409	0.188	0.191
qla5re	0.826	−3.792	−3.923	−0.134	−0.139

Table 1: Quadrupole comparison at R-rot Region

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Name	s at exit (m)	length(m)	b2	K2L	Beta.a	Beta.b	Eta.x	Eta.y	Phase .a	Phase.b
SLYTLE	28.102	0.6	4.201	8.402	3.20	2263.099	−0.172	−0.00000432	2.780	4.713
SLYTLE#1	54.694	0.3	2.101(scaled)	4.201	3.226	2279.808	−0.166	0.000182	5.828	7.854
SLYTLE#2	54.994	0.3	2.101(scaled)	4.201	3.308	2296.587	−0.160	0.000183	5.920	7.854
SLYTRE	2961.822	0.6	−4.530	−9.061	1.762	2212.504	0.160	−0.0000926	280.138	265.899
SLYTRE#1	2988.613	0.3	−2.265 (scaled)	−4.530	1.617	2371.518	0.151	−0.00000272	283.101	269.0404
SLYTRE#2	2988.913	0.3	−2.265 (scaled)	−4.530	1.586	2536.041	0.142	−0.00000267	283.290	269.040

Table 2: Sly sextupole information

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Spin Rotator Component	Solenoid	Length (m)	Strength (T)
L-rot	BLA4LE	5.902	4.526
	BLA4LE	5.902	4.526
	B2E	5.902	0.799
R-rot	B2E	5.902	−3.778
	B2E	5.902	−3.778

Table 3: Solenoid Information

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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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