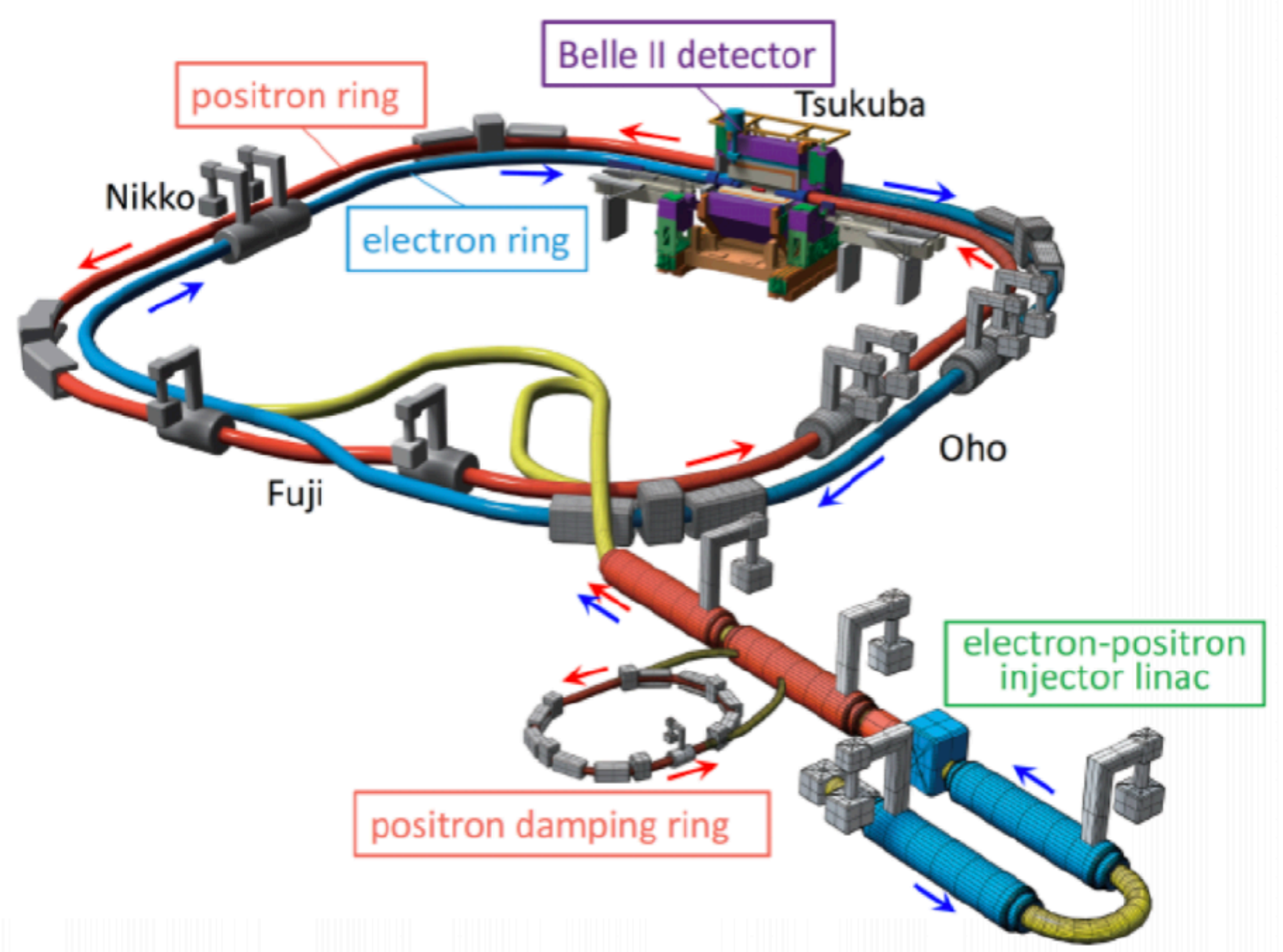
Spin Rotator Design for the SuperKEKB High Energy Ring in a Proposed Polarization Upgrade



Yuhao Peng

2021.07.16

Outline

- Brief review of this project
- Spin information
- Technical details to be confirmed
- Beam Tracking Progress

Purpose

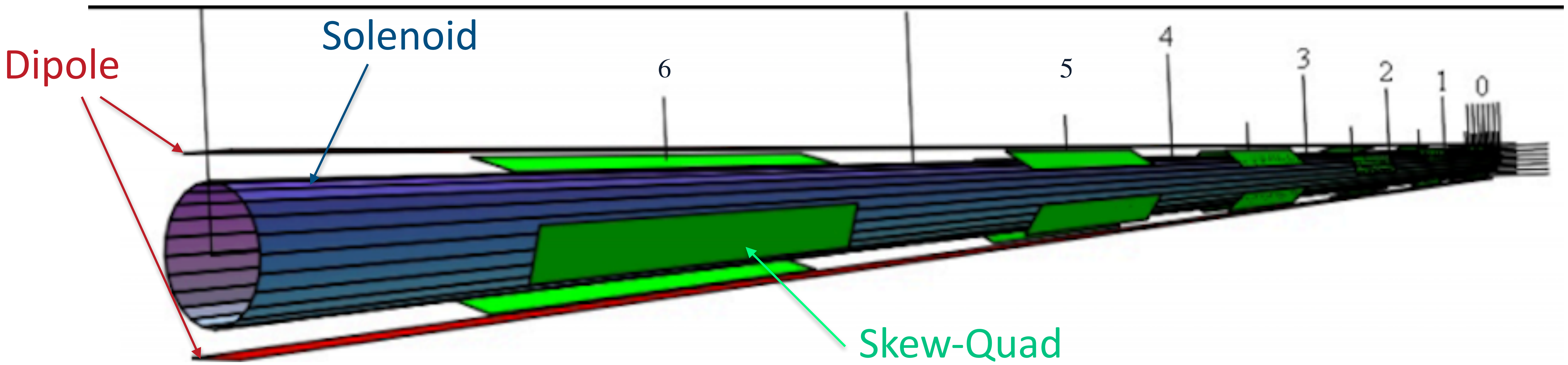
Design a spin rotator for SuperKEKB High Energy Ring, to polarize the spin of the electron beam in the longitudinal direction at the interaction point (IP)

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

University of Victoria

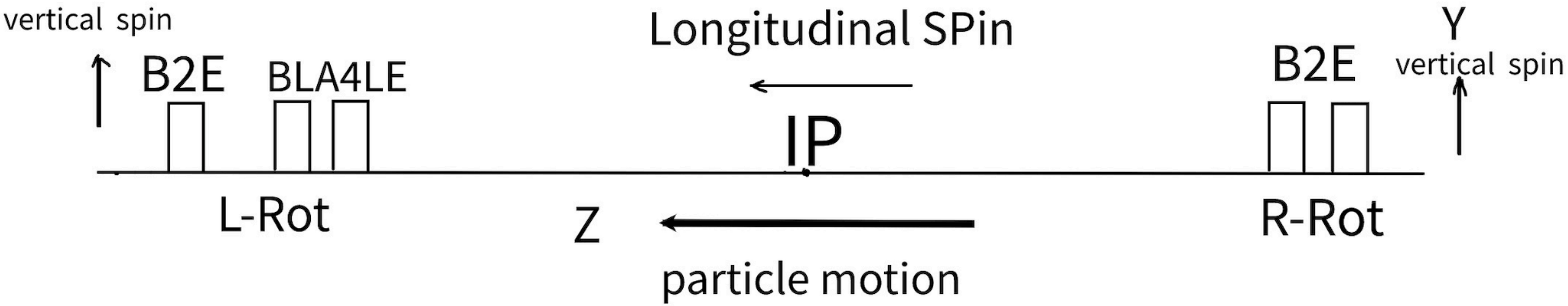
Rotator Magnet

- 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



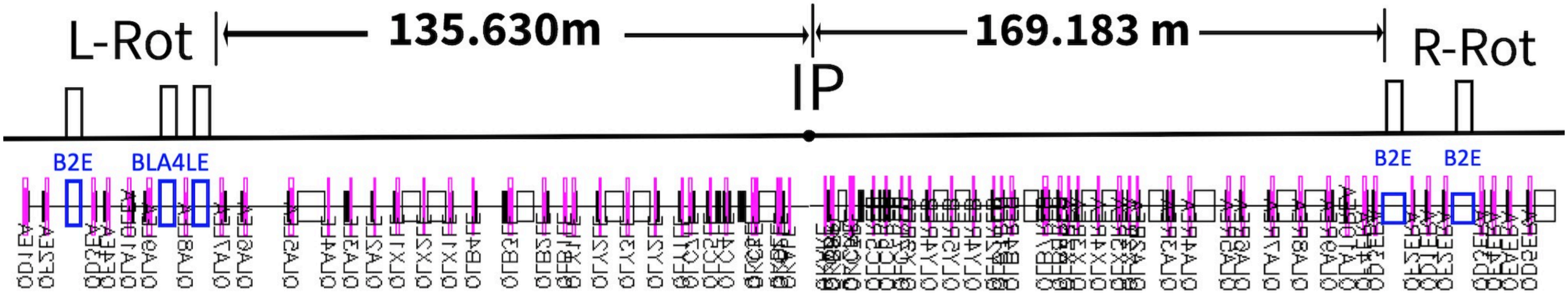
University of Victoria

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



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

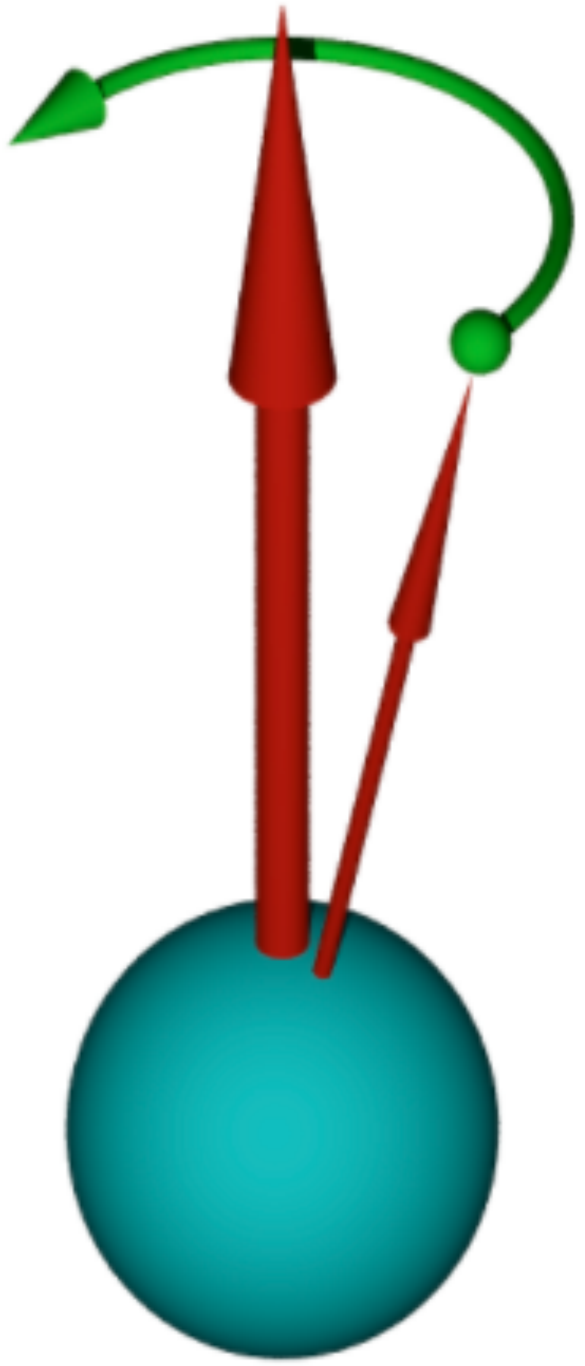
~ 9.62°counterclockwise in the x-z plane (positron)

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

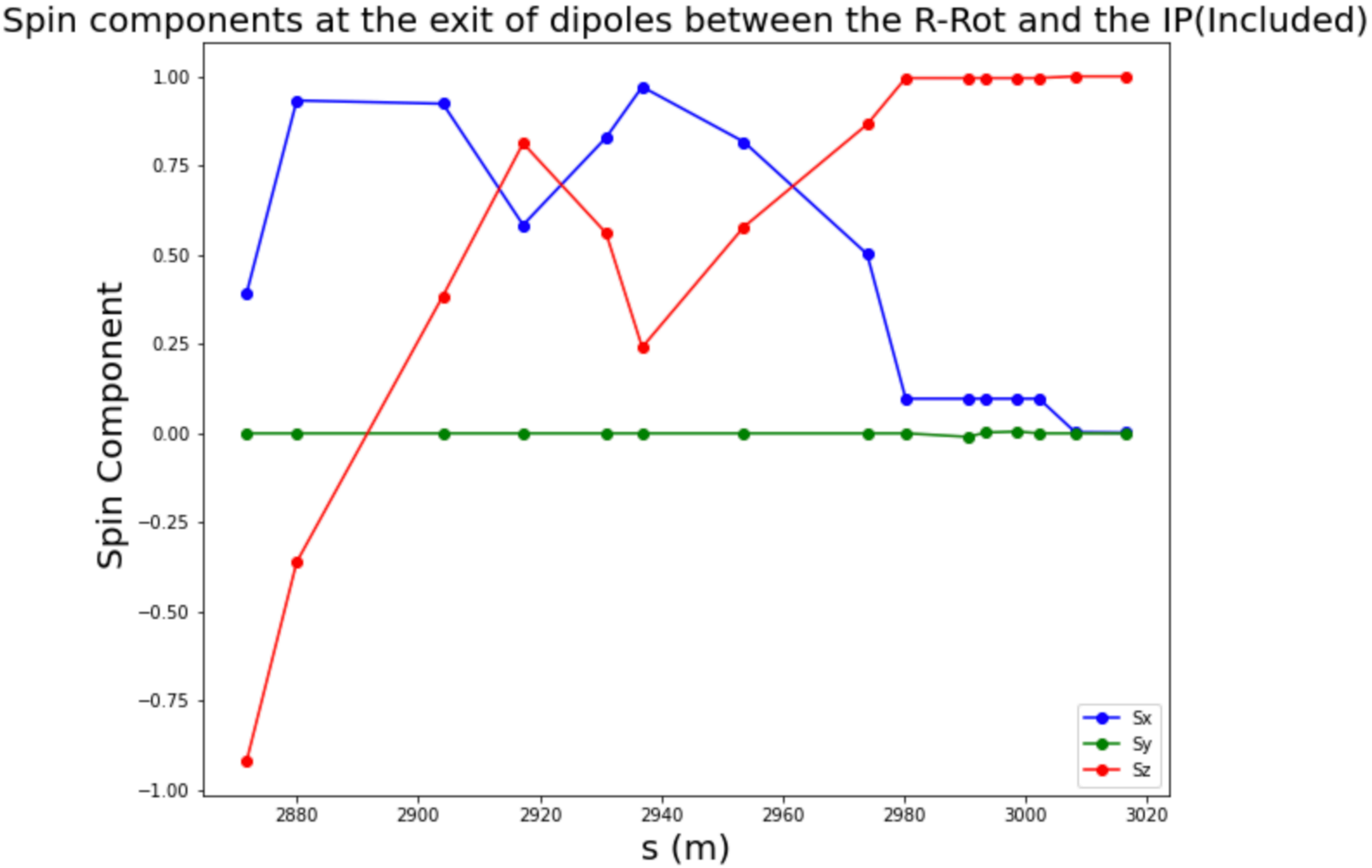
~ 157.46° clockwise in the x-z plane (positron)

Spin Precession in the Dipole Field

$$\frac{d\vec{s}}{ds} = \frac{q}{p}(1 + a\gamma)\vec{S} \times \vec{B}_{\perp} \qquad \vec{\Omega} = -\frac{q}{m\gamma}(1 + a\gamma)\vec{B}_{\perp}$$

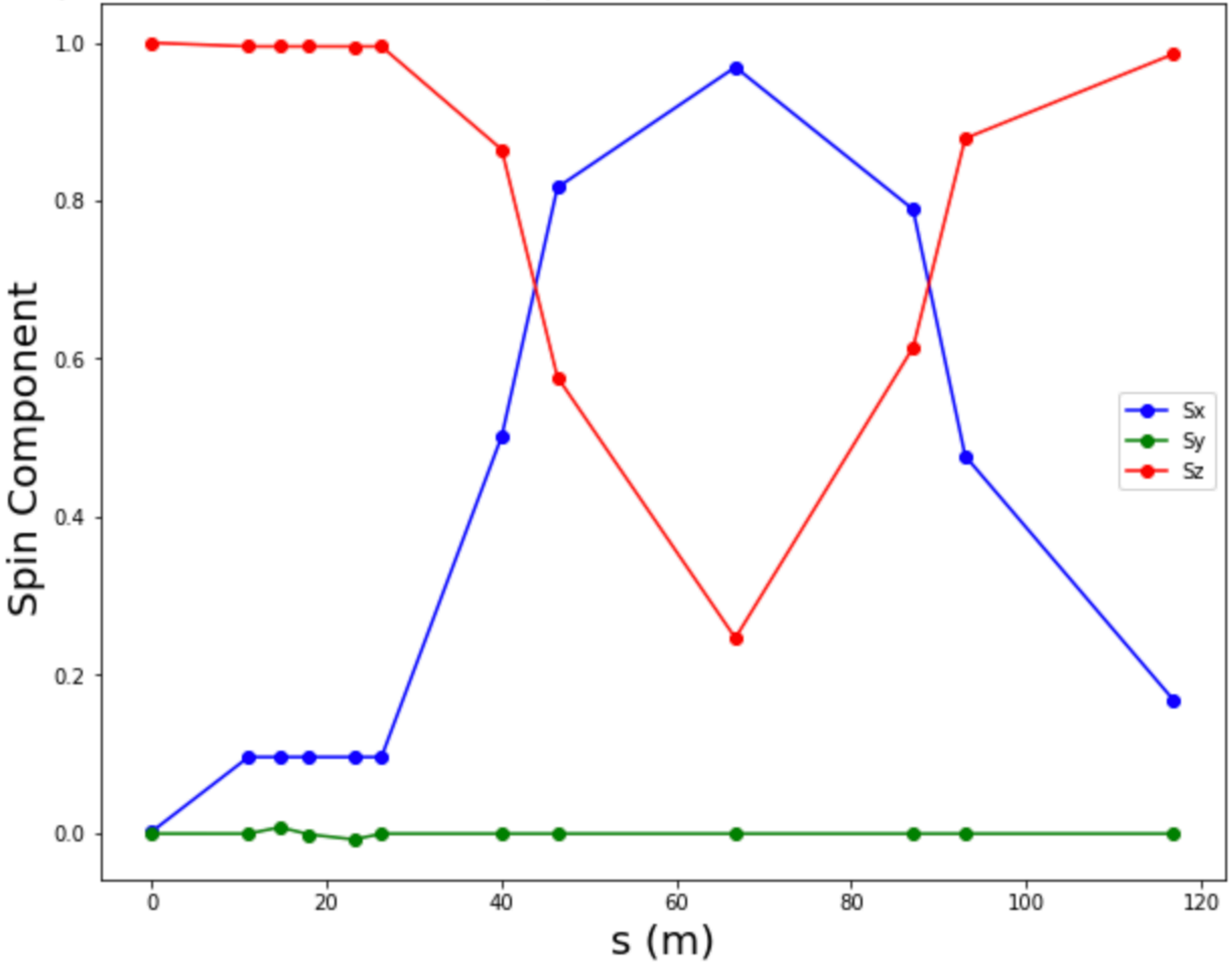


- The axial vector is aligned with the dipole field if the particle carries negative charge
- anti-aligned for positively charged particle



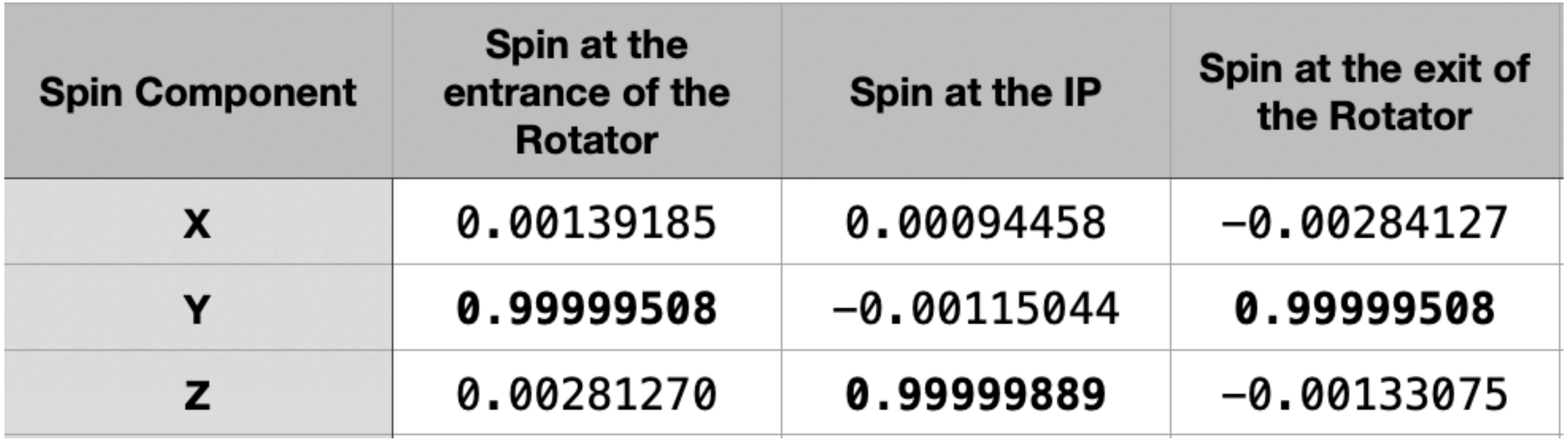
University of Victoria

Spin components at the exit of dipoles between the L-Rot and the IP(Included)



Longitudinal spin alignment

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



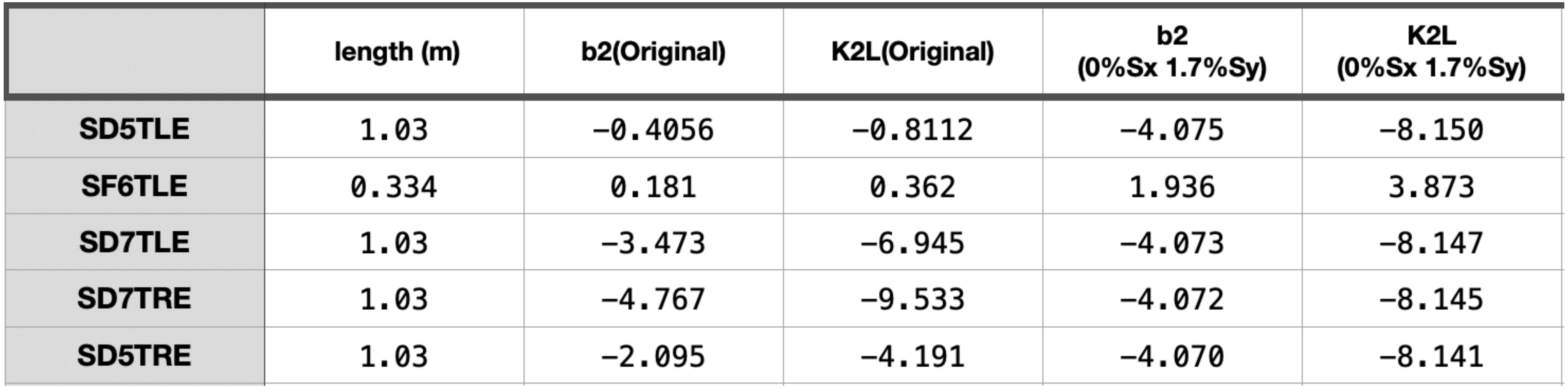
Spin Component	Spin at the entrance of the Rotator	Spin at the IP	Spin at the exit of the Rotator
X	0.00139185	0.00094458	−0.00284127
Y	**0.99999508**	−0.00115044	**0.99999508**
Z	0.00281270	**0.99999889**	−0.00133075

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

Previous Plan for Tuning Sextupoles



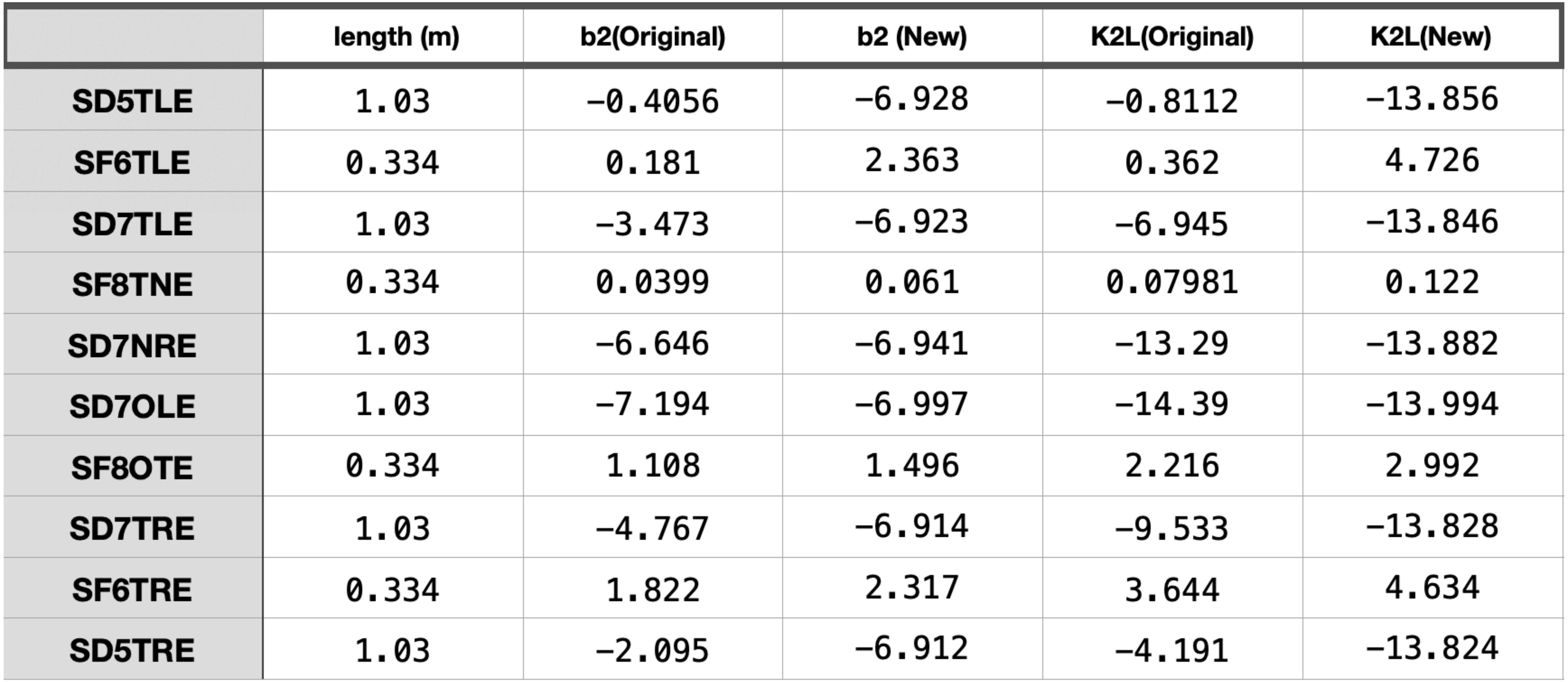
	length (m)	b2(Original)	K2L(Original)	b2 (0%Sx 1.7%Sy)	K2L (0%Sx 1.7%Sy)
SD5TLE	1.03	-0.4056	-0.8112	-4.075	-8.150
SF6TLE	0.334	0.181	0.362	1.936	3.873
SD7TLE	1.03	-3.473	-6.945	-4.073	-8.147
SD7TRE	1.03	-4.767	-9.533	-4.072	-8.145
SD5TRE	1.03	-2.095	-4.191	-4.070	-8.141

- 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?   No, important to crab waist

- Are these SD sextupoles the same type of magnet? YES

Sextupoles Tuning Without Touching Sly

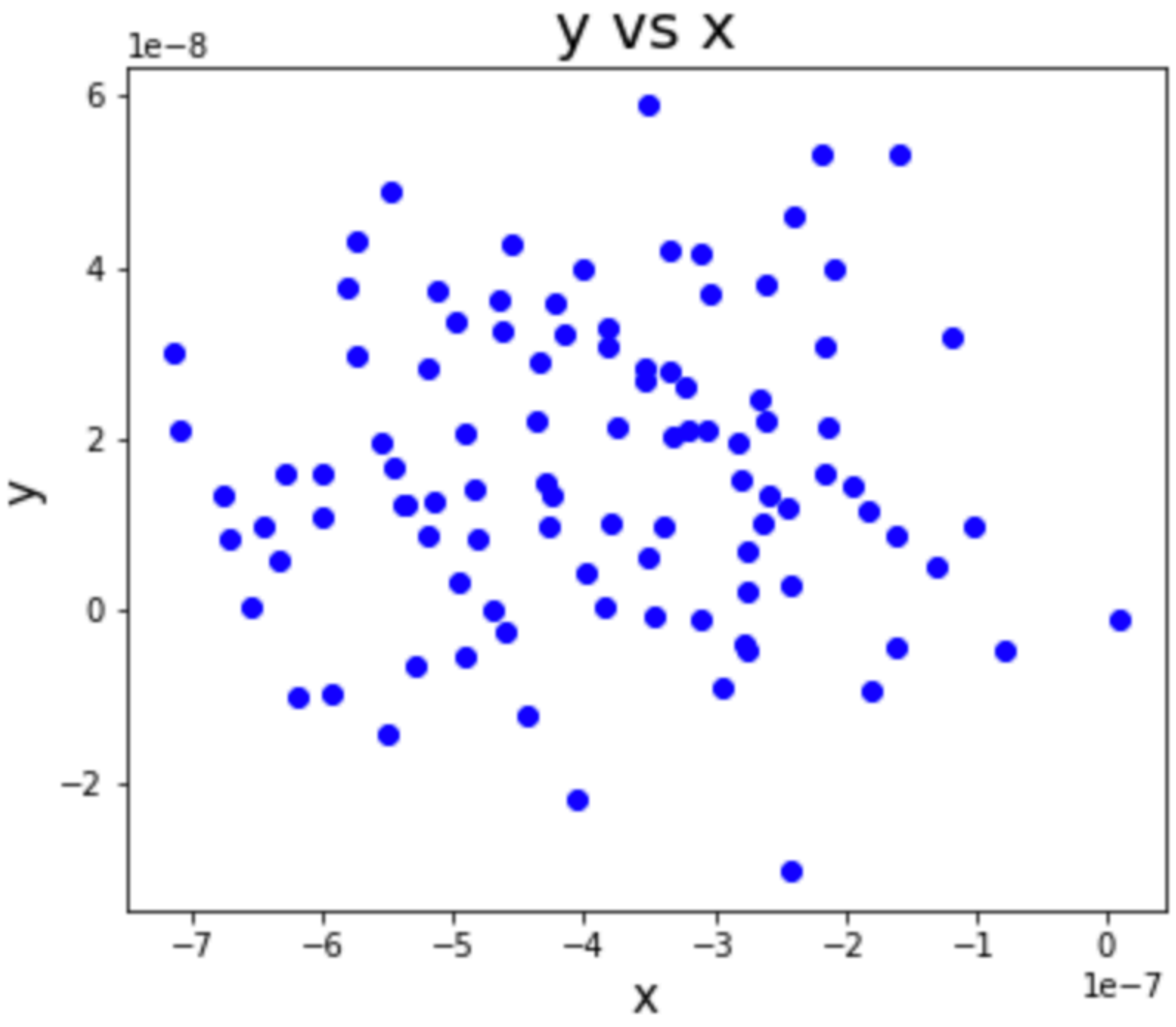


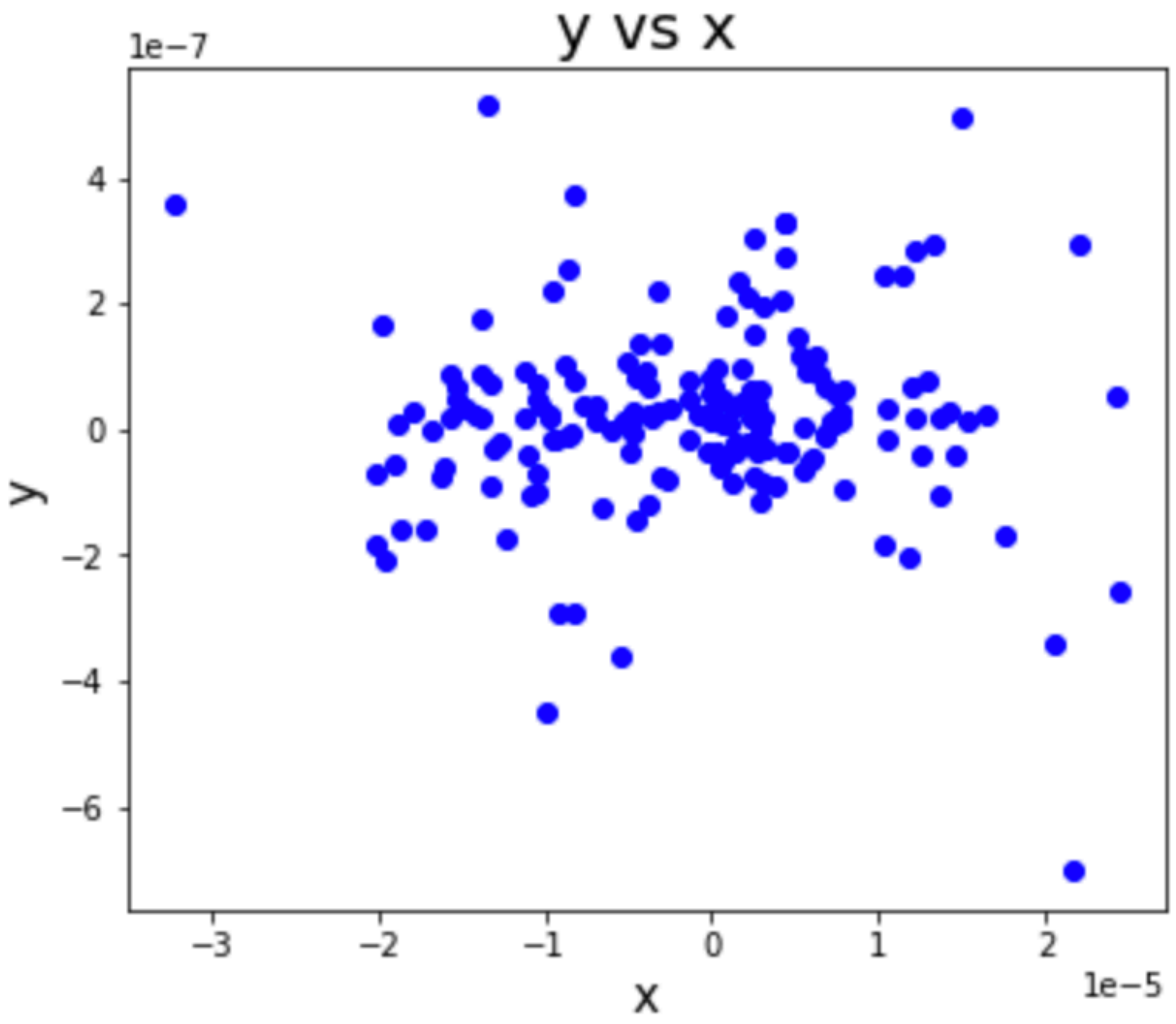
	length (m)	b2(Original)	b2 (New)	K2L(Original)	K2L(New)
SD5TLE	1.03	−0.4056	−6.928	−0.8112	−13.856
SF6TLE	0.334	0.181	2.363	0.362	4.726
SD7TLE	1.03	−3.473	−6.923	−6.945	−13.846
SF8TNE	0.334	0.0399	0.061	0.07981	0.122
SD7NRE	1.03	−6.646	−6.941	−13.29	−13.882
SD7OLE	1.03	−7.194	−6.997	−14.39	−13.994
SF8OTE	0.334	1.108	1.496	2.216	2.992
SD7TRE	1.03	−4.767	−6.914	−9.533	−13.828
SF6TRE	0.334	1.822	2.317	3.644	4.634
SD5TRE	1.03	−2.095	−6.912	−4.191	−13.824

The original strongest SF[b2] = 2.4, L =0.334m

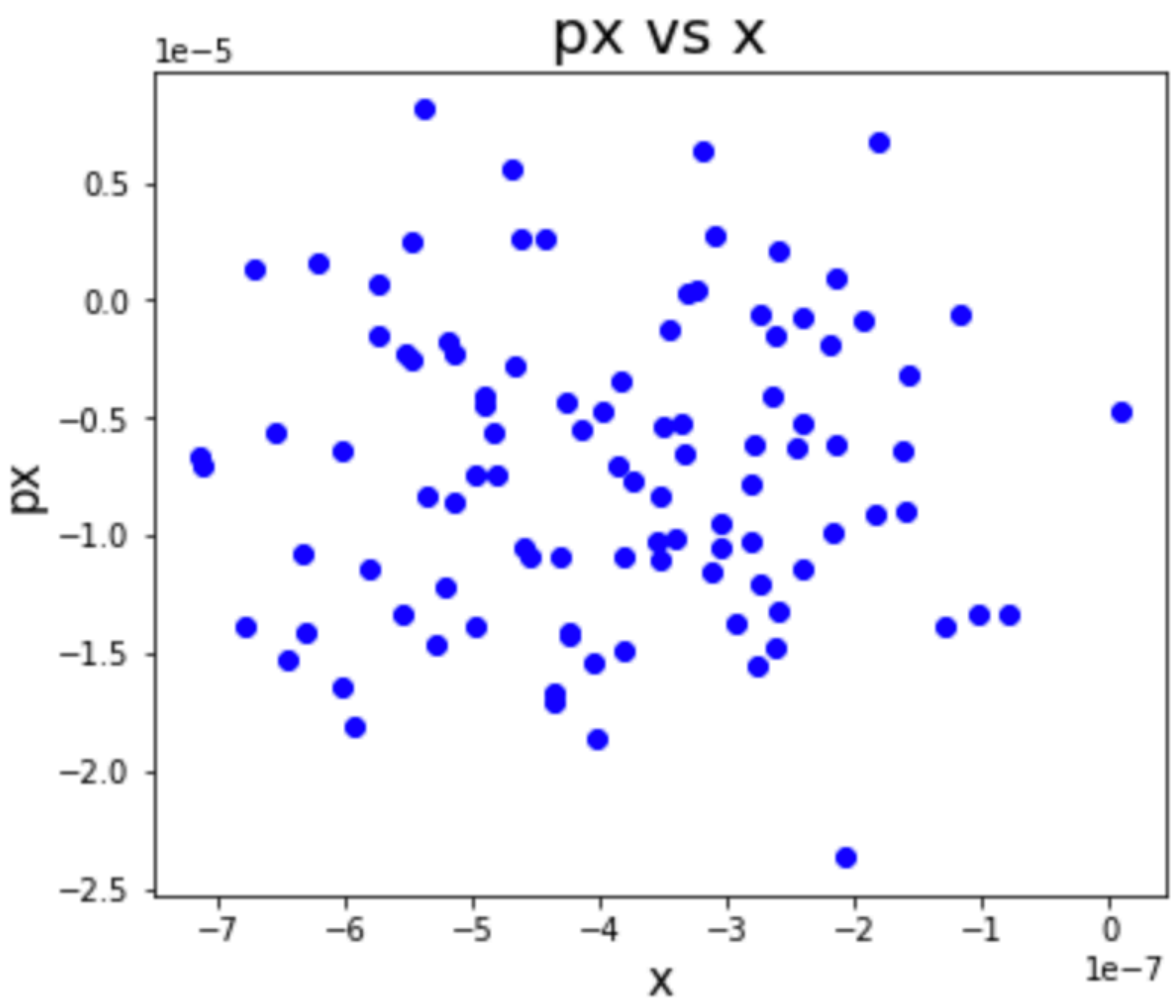
SD[b2] = -7.2, L = 1.03m

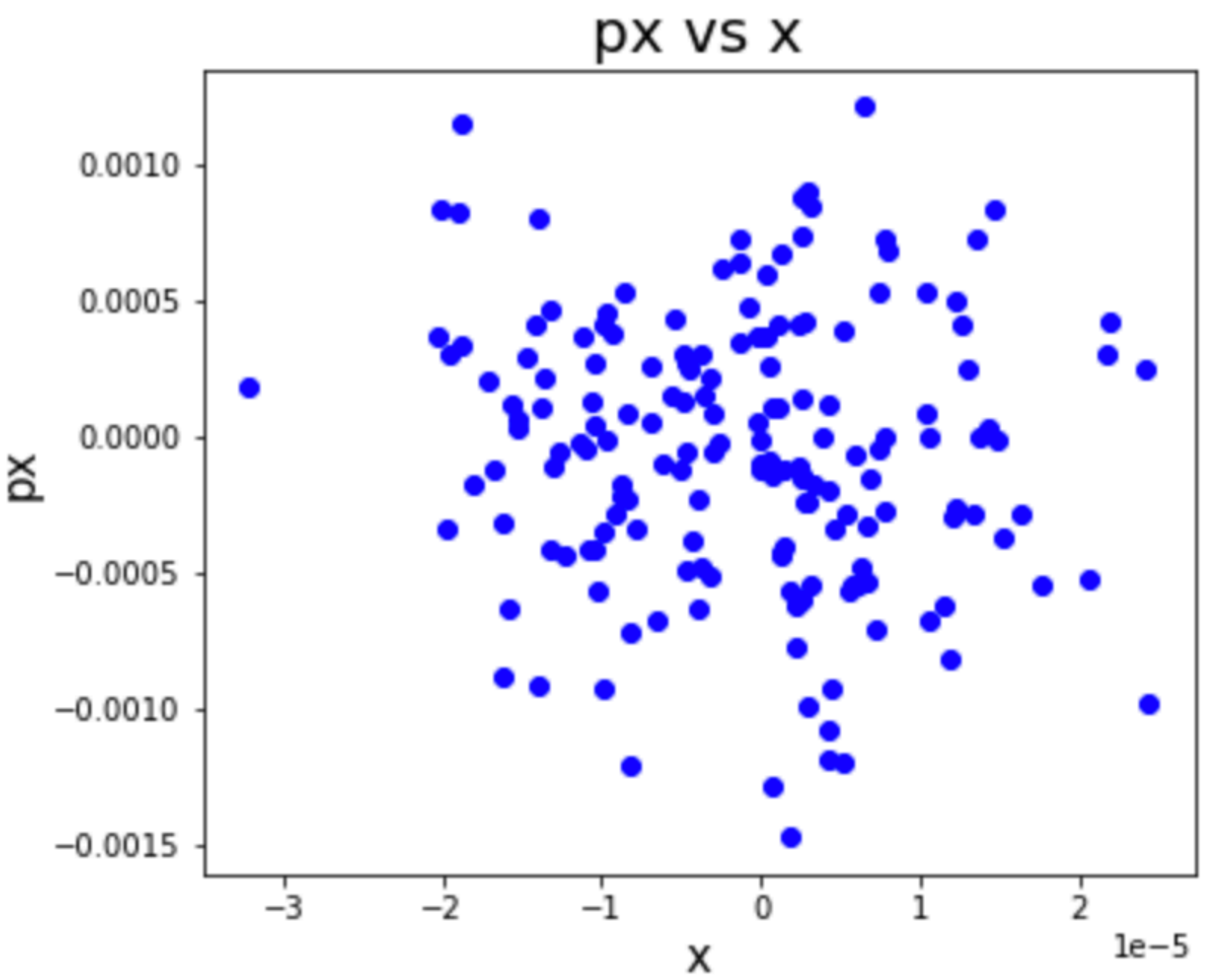
Tracking 200 particles for 5000 turns in the Rot lattice



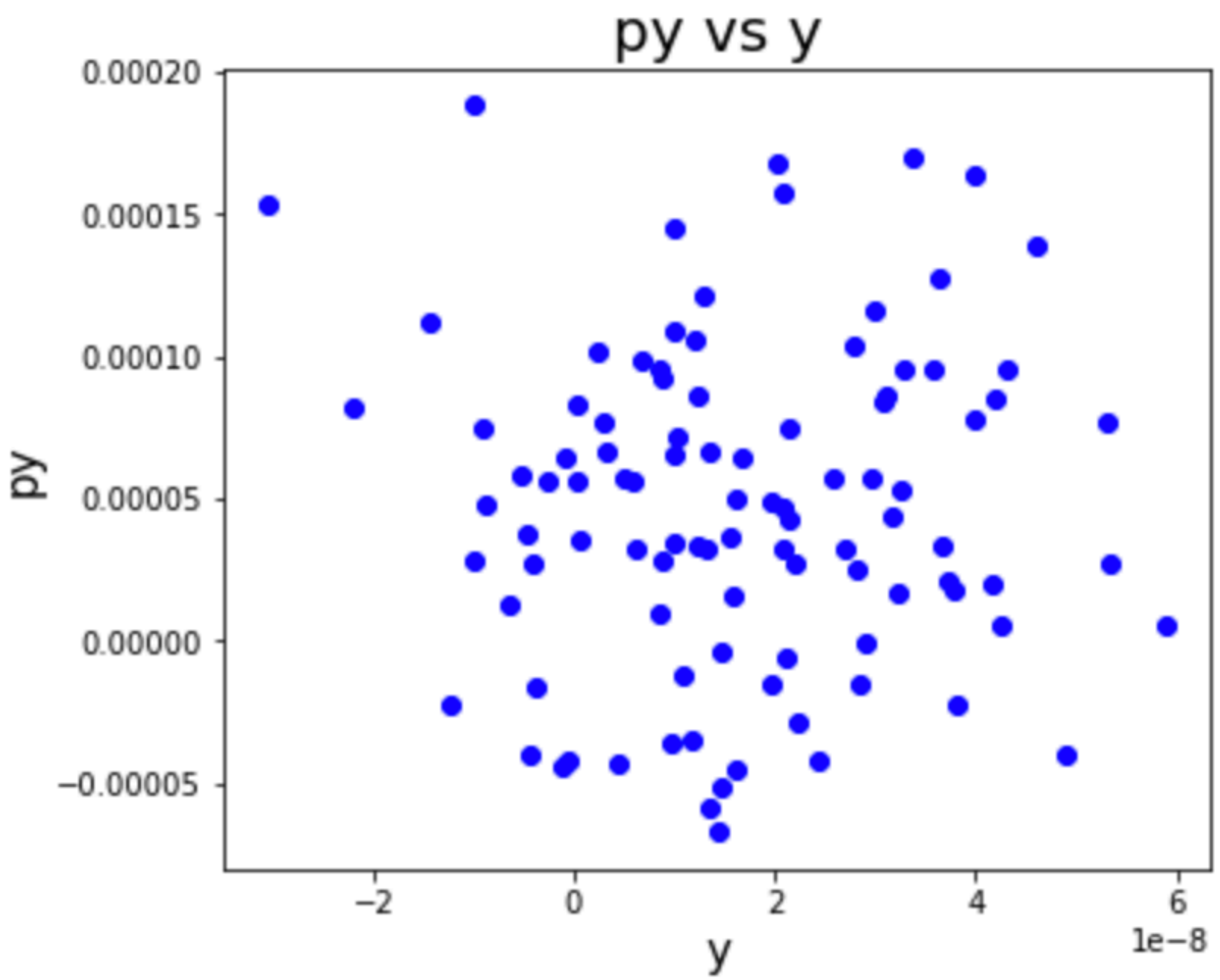


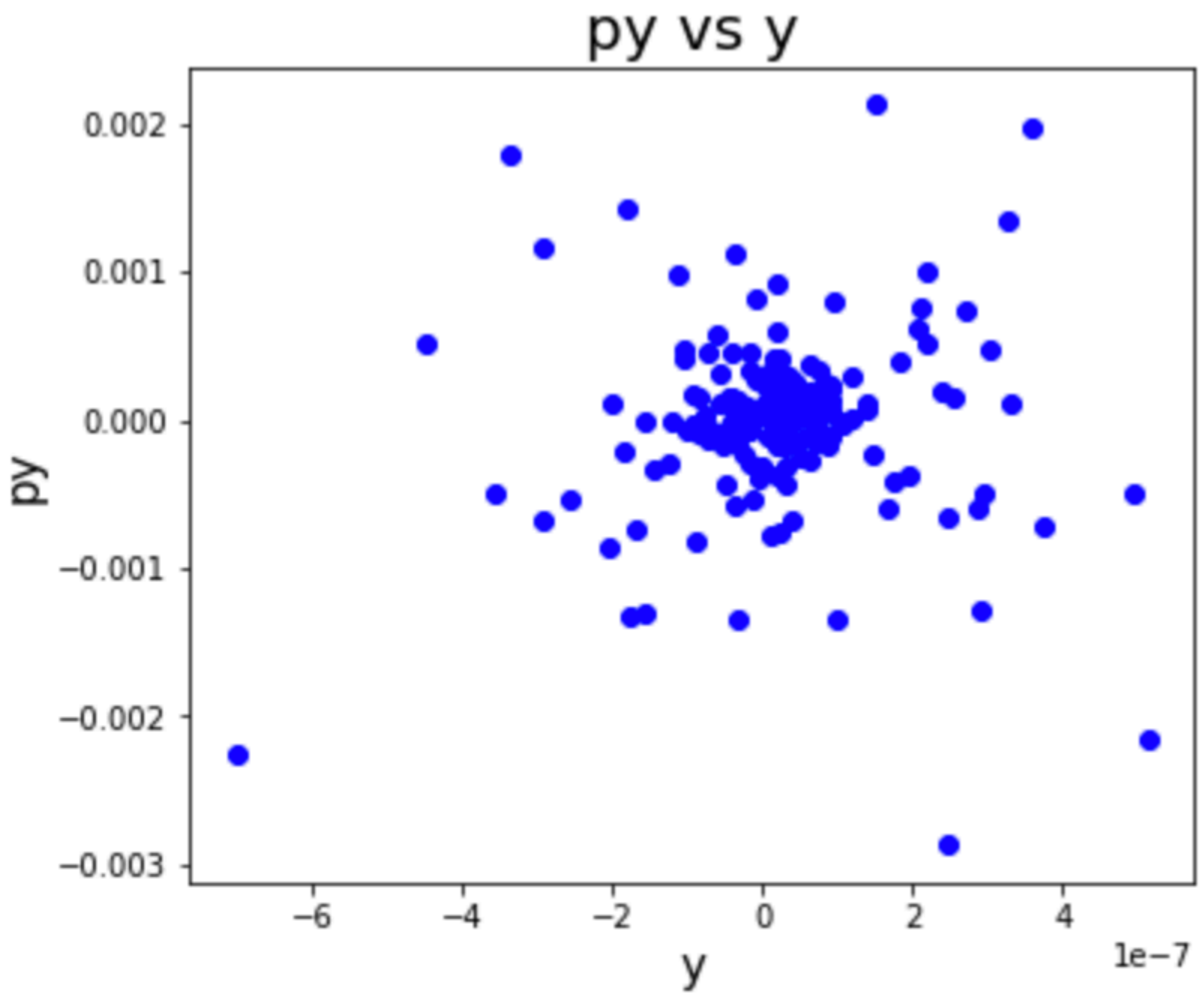
Turn: 0 5000


px vs x
1e−5
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
px
−7
−6
−5
−4
−3
−2
−1
0
1e−7
x

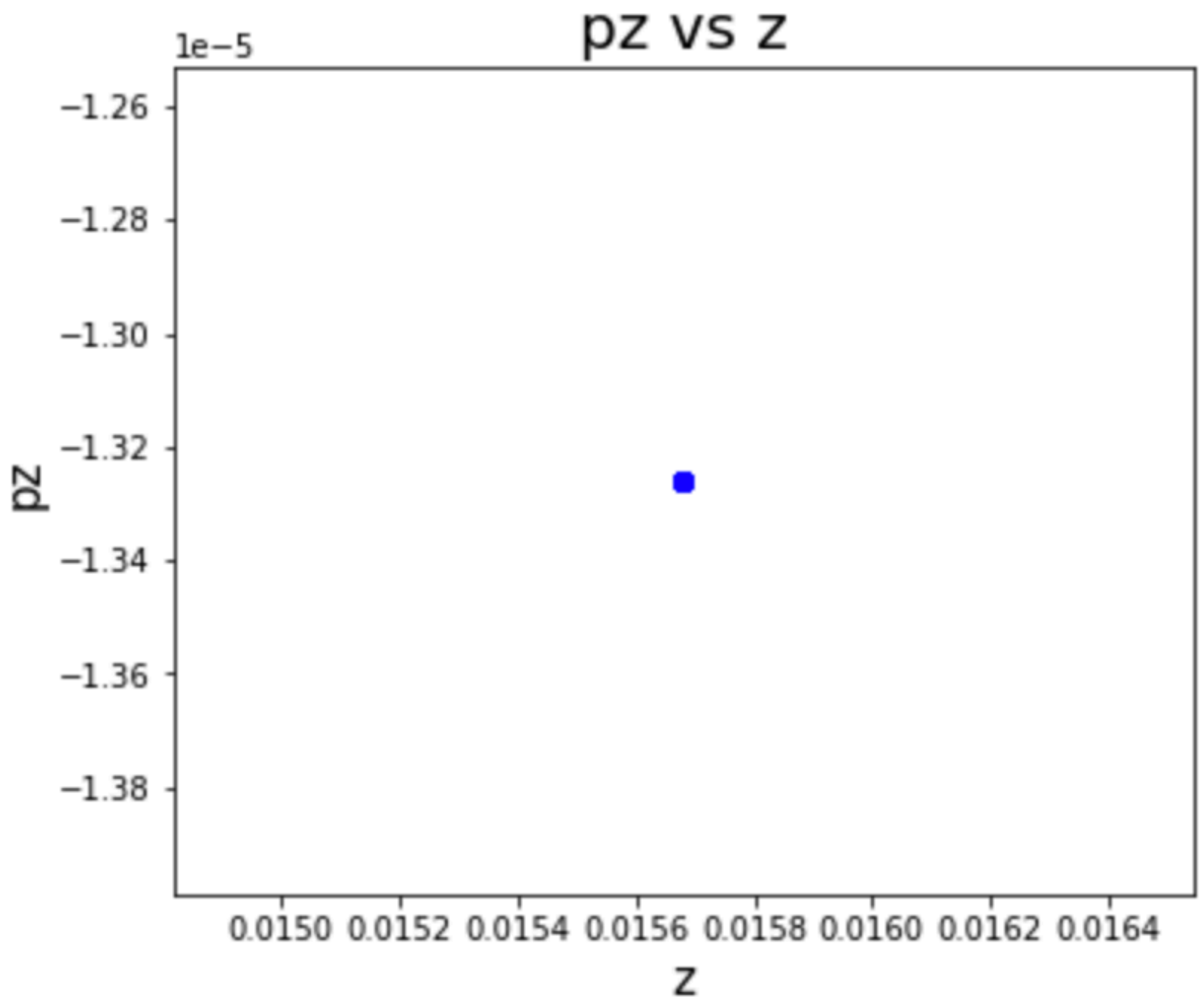

px vs x
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
px
−3
−2
−1
0
1
2
1e−5
x

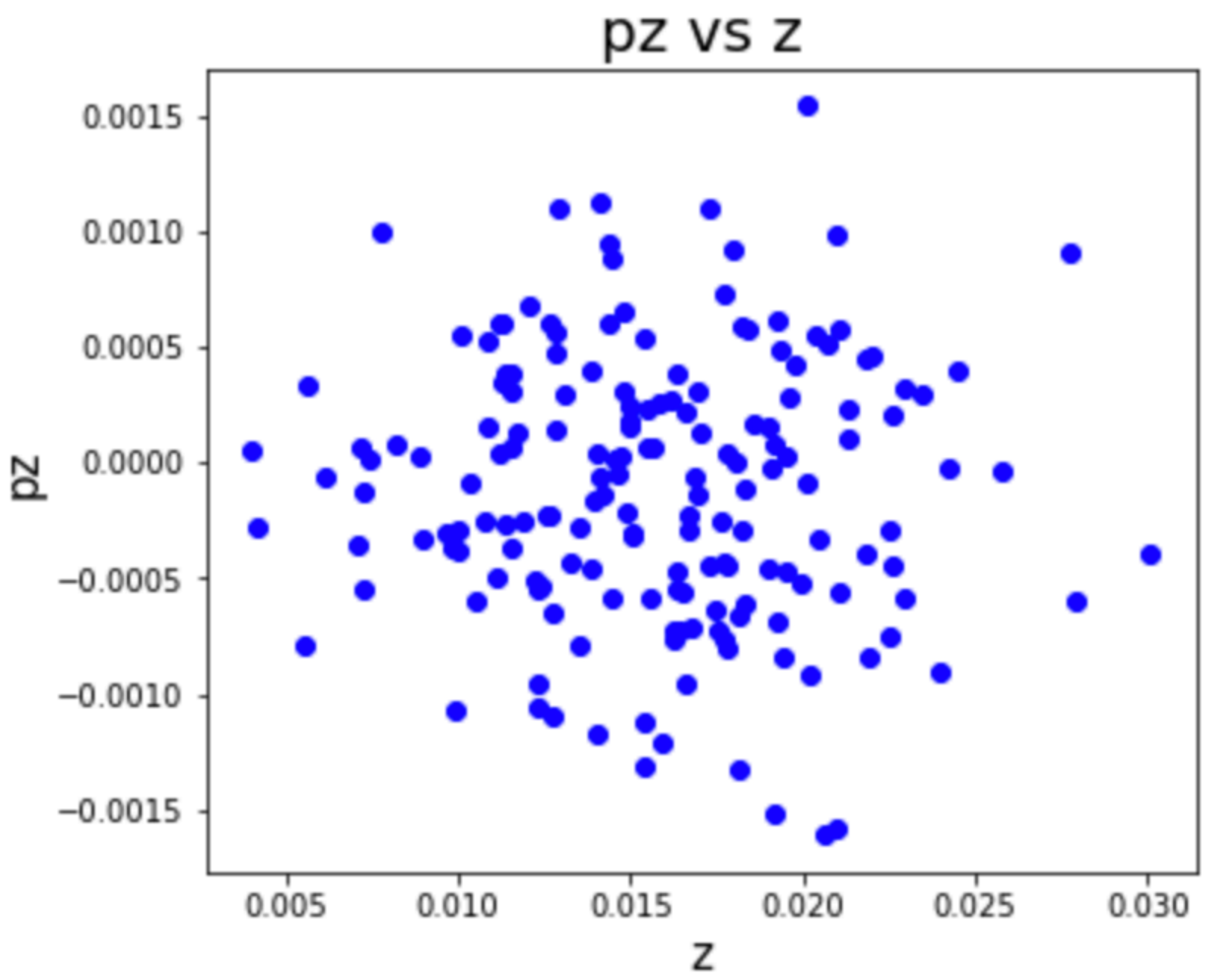
Turn: 0 5000


py vs y
0.00020
0.00015
0.00010
0.00005
0.00000
−0.00005
py
−2
0
2
4
6
1e−8
y


py vs y
0.002
0.001
0.000
−0.001
−0.002
−0.003
py
−6
−4
−2
0
2
4
1e−7
y

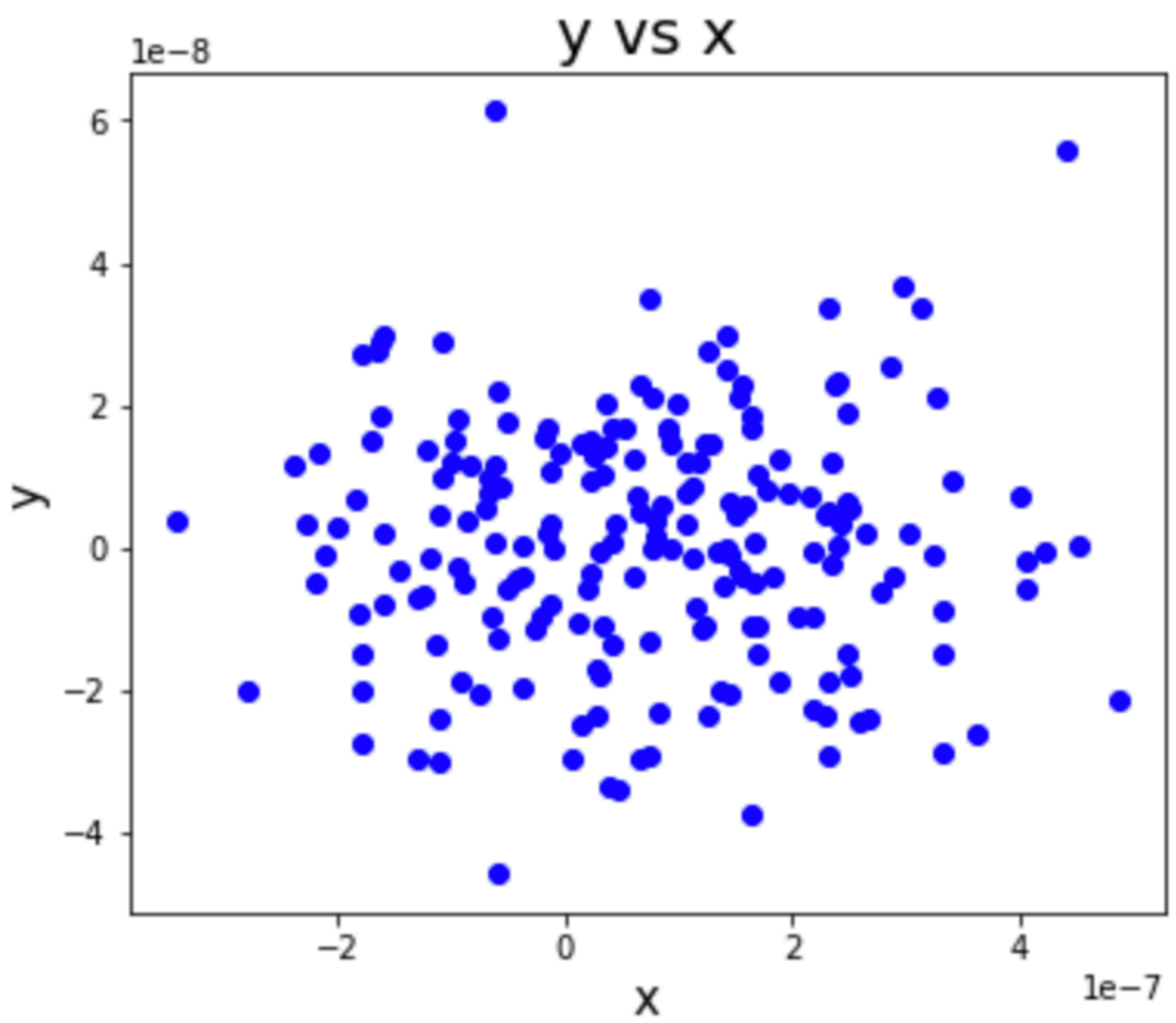
Turn: 0 5000

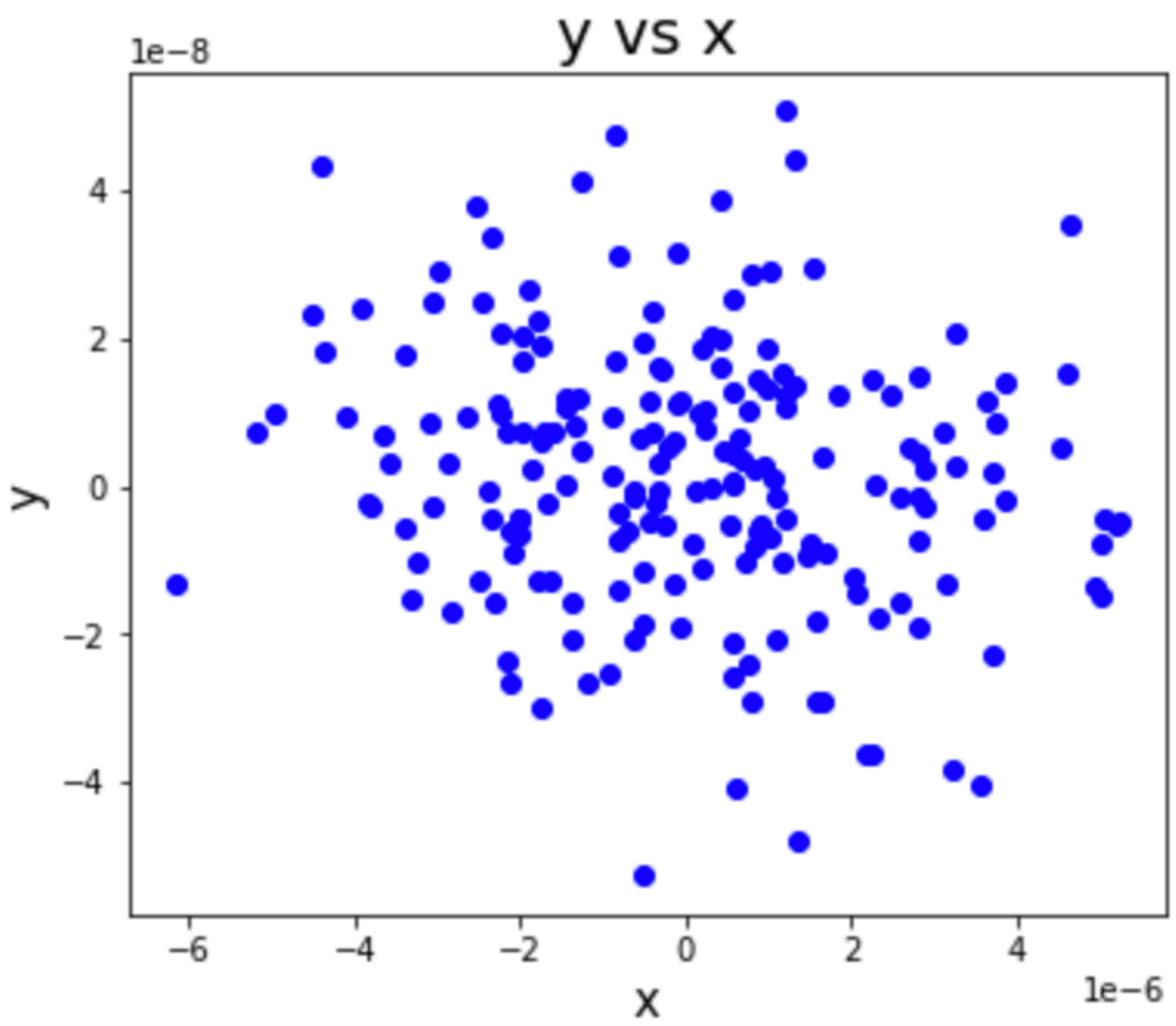

pz vs z
1e−5
−1.26
−1.28
−1.30
−1.32
−1.34
−1.36
−1.38
pz
0.0150
0.0152
0.0154
0.0156
0.0158
0.0160
0.0162
0.0164
z


pz vs z
0.0015
0.0010
0.0005
0.0000
−0.0005
−0.0010
−0.0015
pz
0.005
0.010
0.015
0.020
0.025
0.030
z

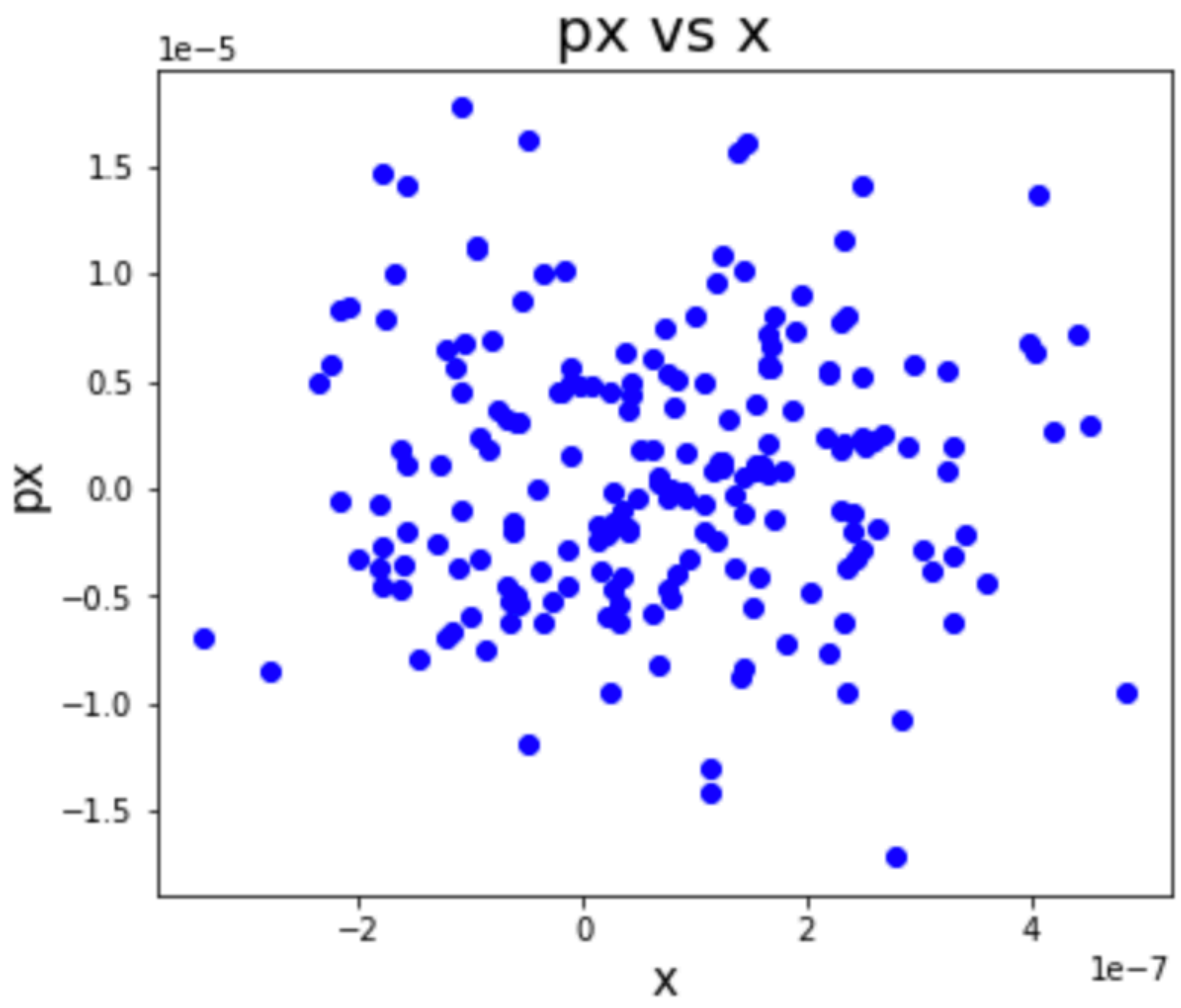
Turn: 0 5000

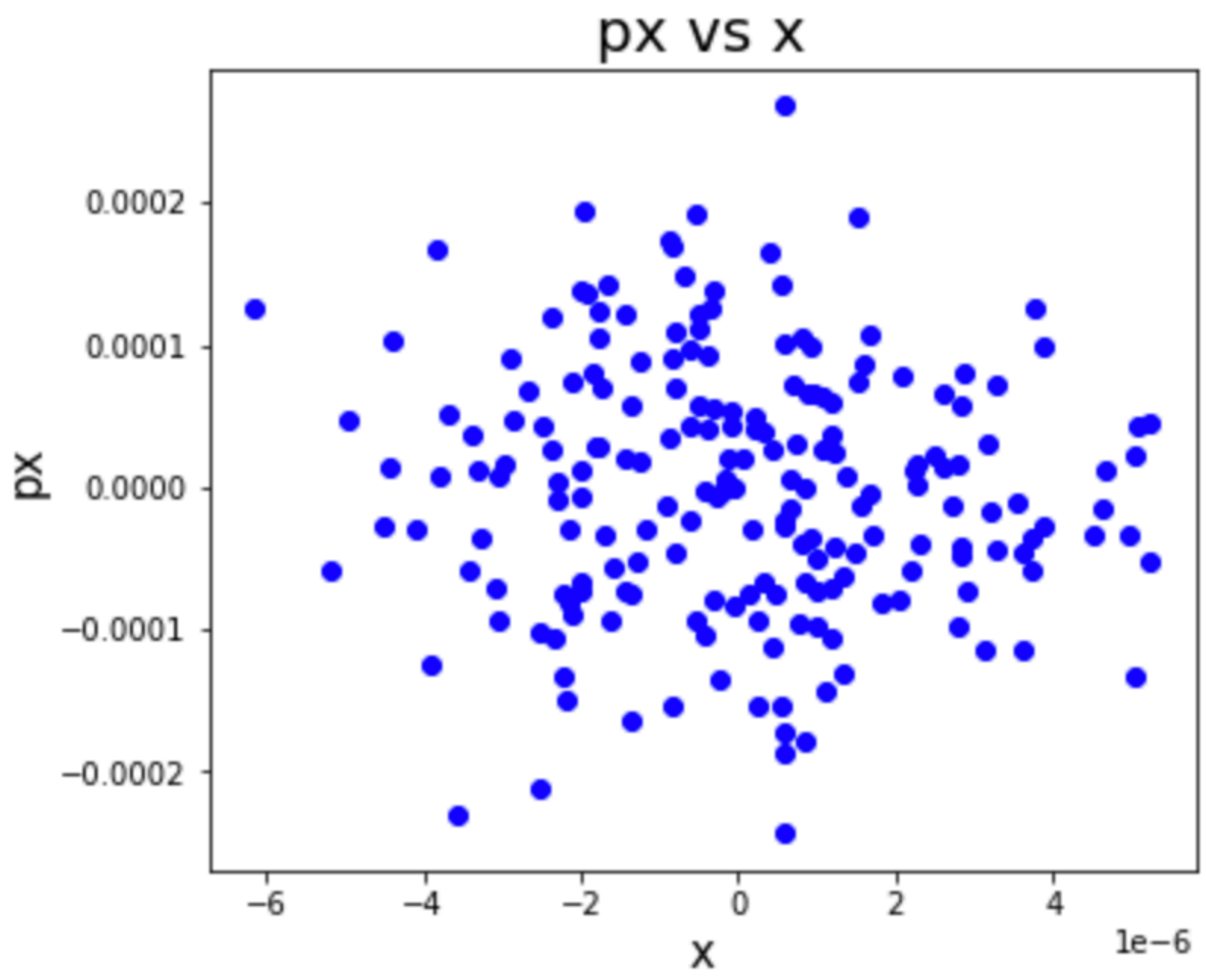
Tracking 200 particles for 10 turns in the Original lattice



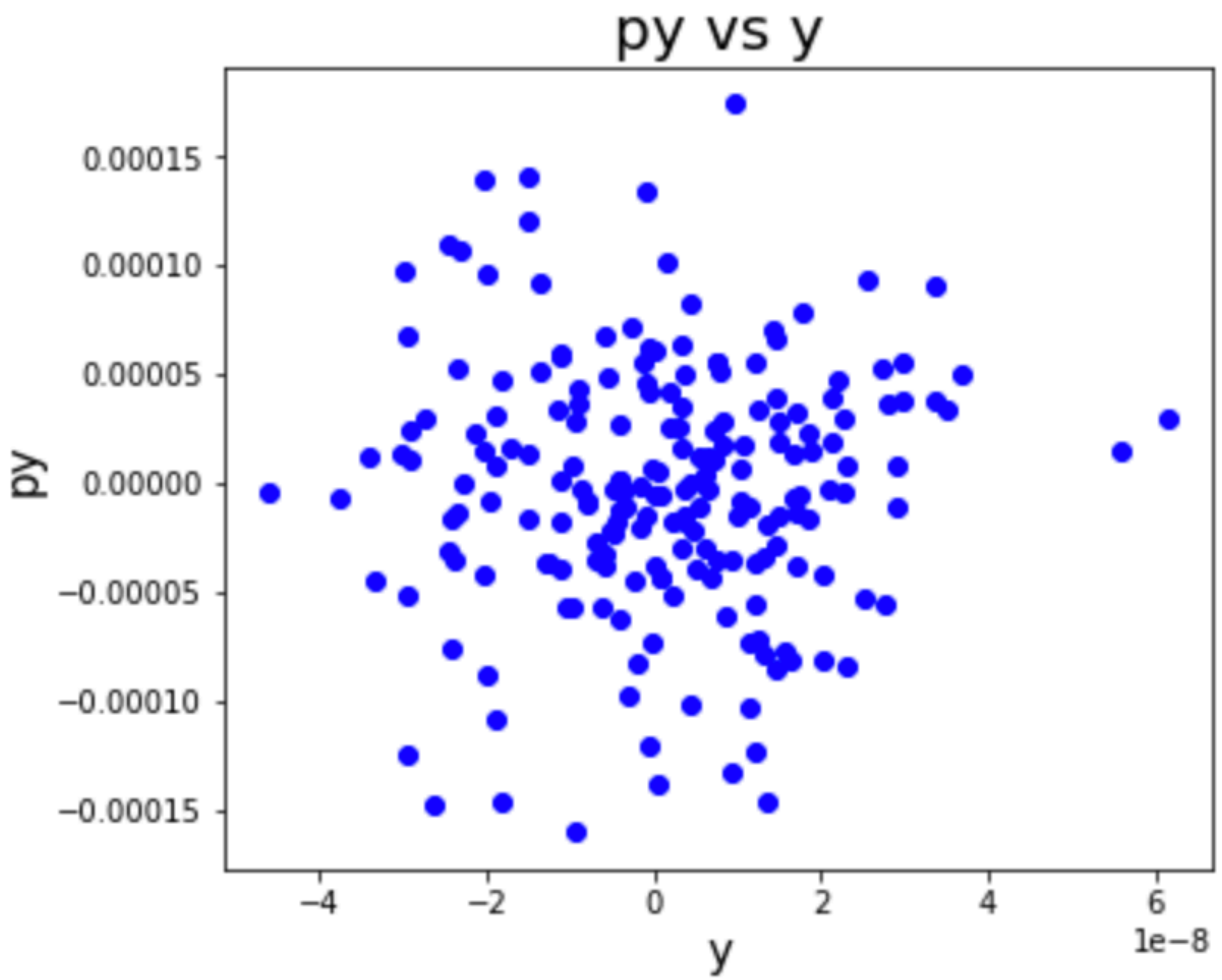


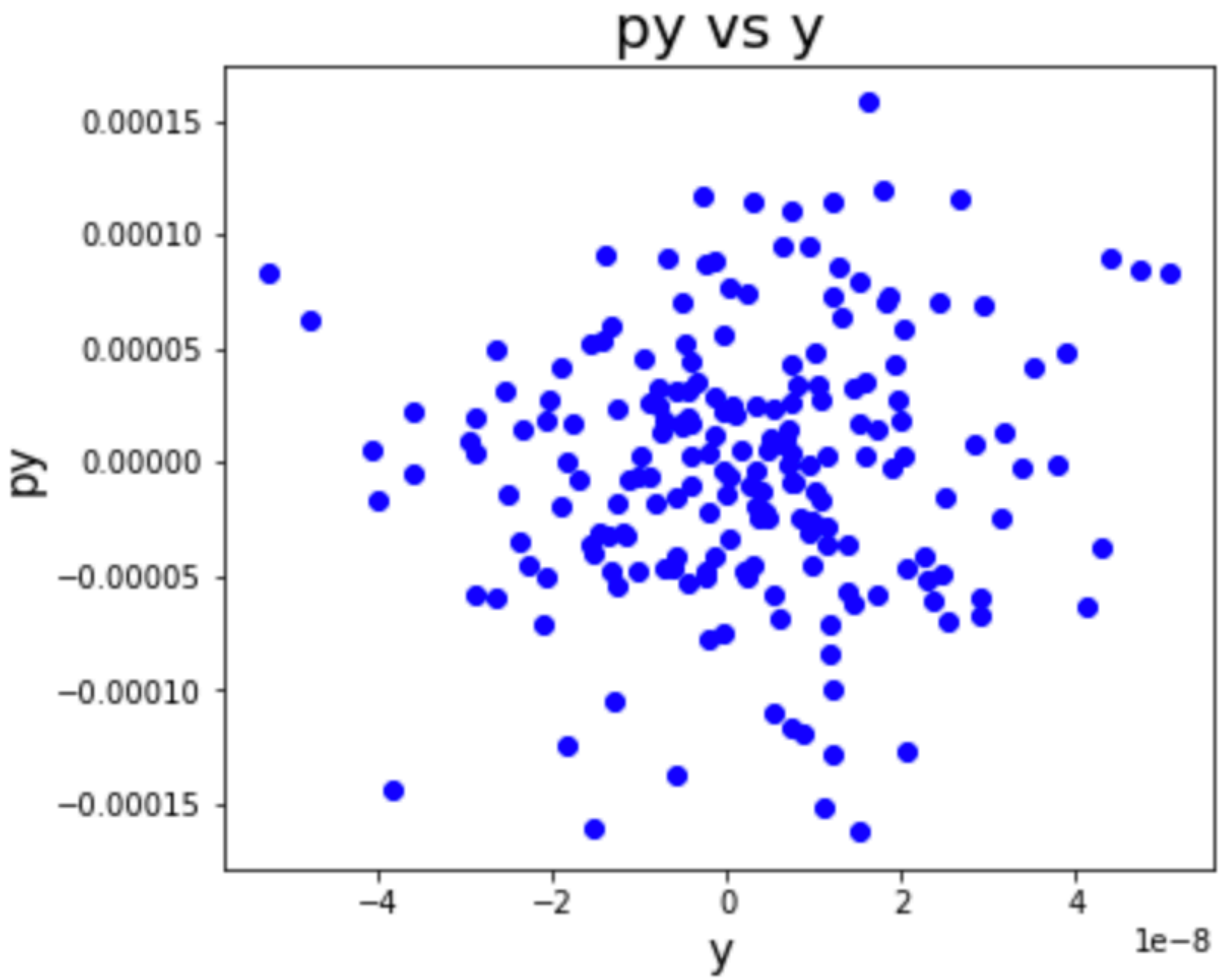
Turn: 0 10


px vs x
1e−5
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
px
−2
0
2
4
1e−7
x

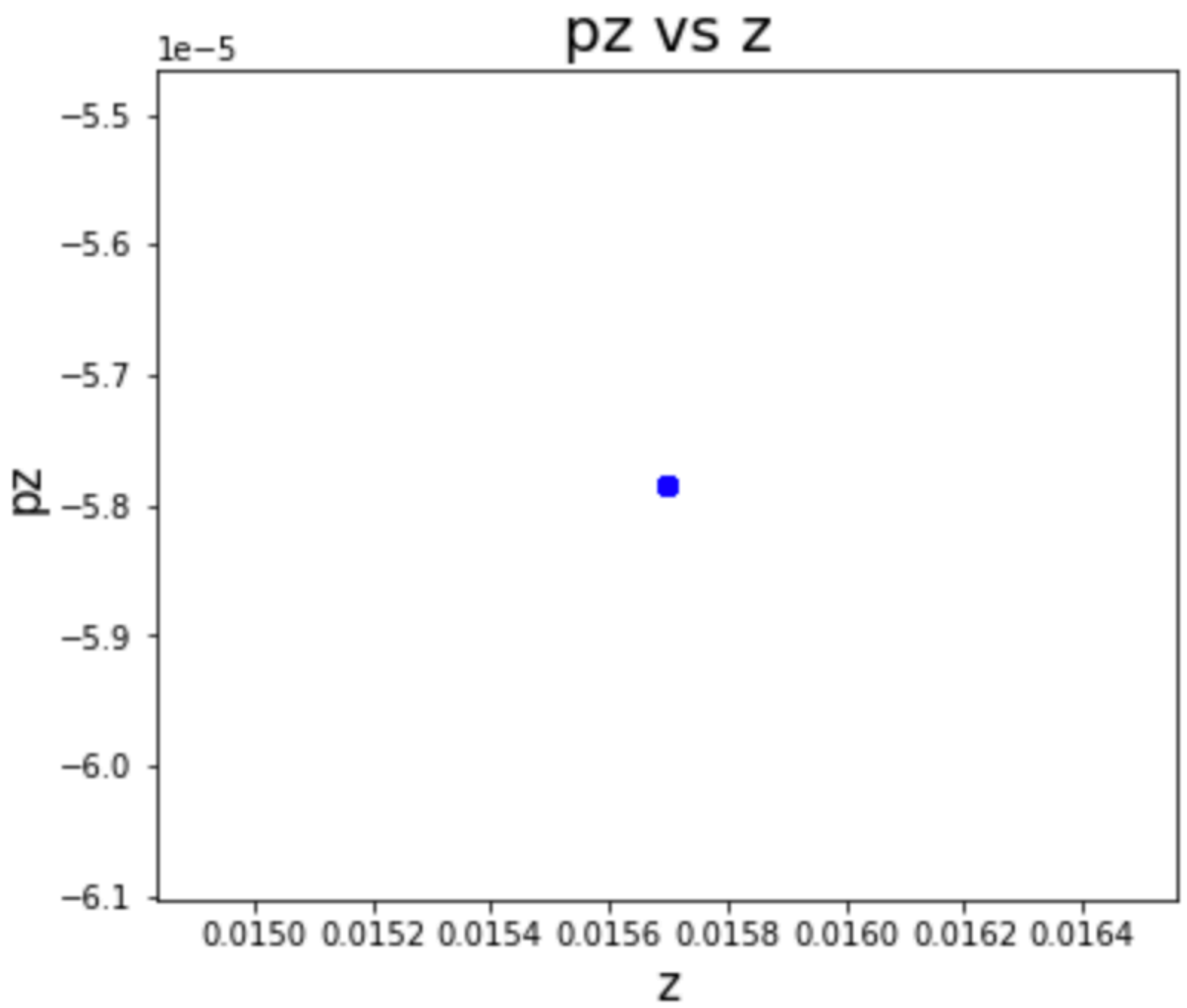

px vs x
0.0002
0.0001
0.0000
−0.0001
−0.0002
px
−6
−4
−2
0
2
4
1e−6
x

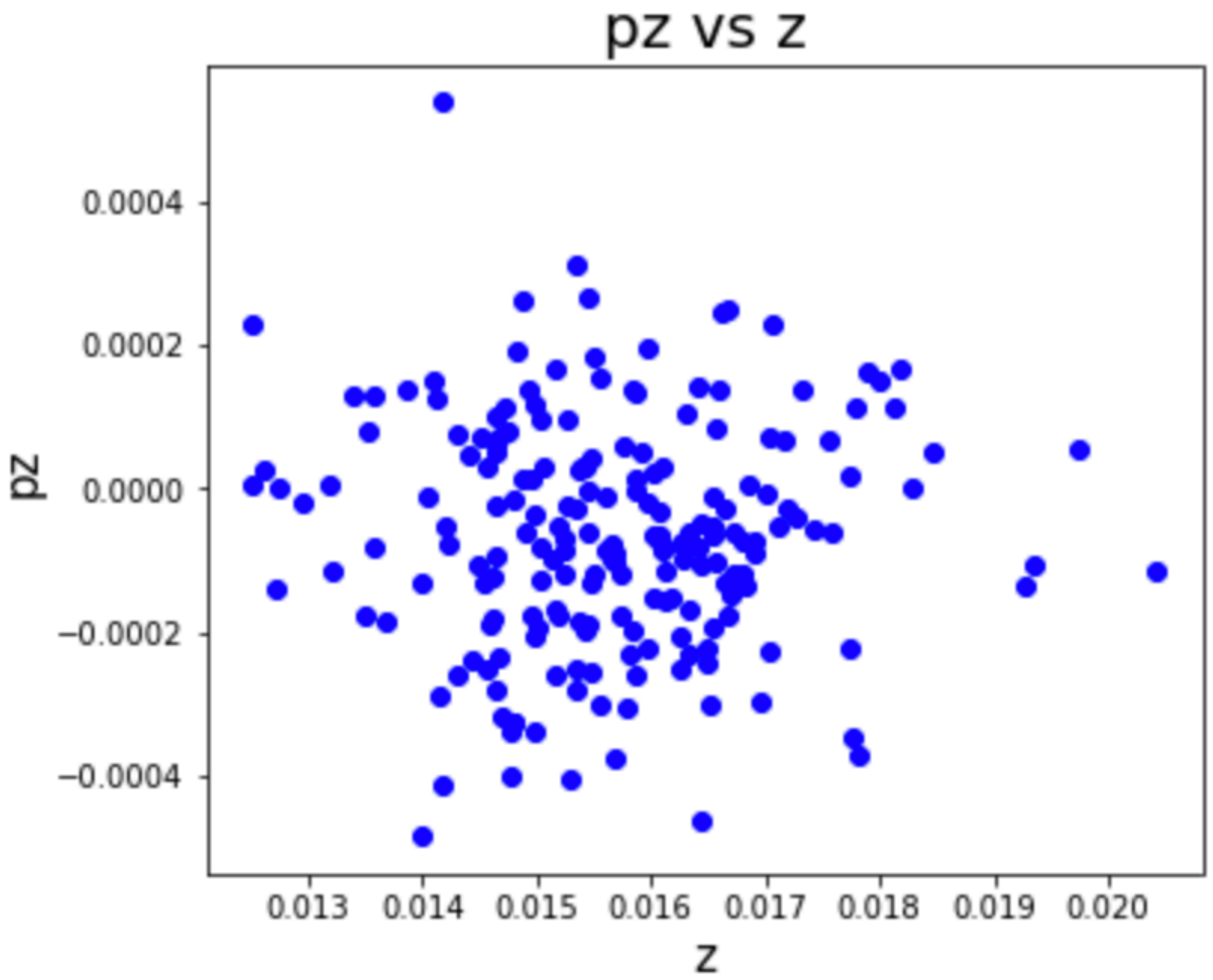
Turn: 0 10


py vs y
0.00015
0.00010
0.00005
0.00000
−0.00005
−0.00010
−0.00015
py
−4
−2
0
2
4
6
1e−8
y


py vs y
0.00015
0.00010
0.00005
0.00000
−0.00005
−0.00010
−0.00015
py
−4
−2
0
2
4
1e−8
y

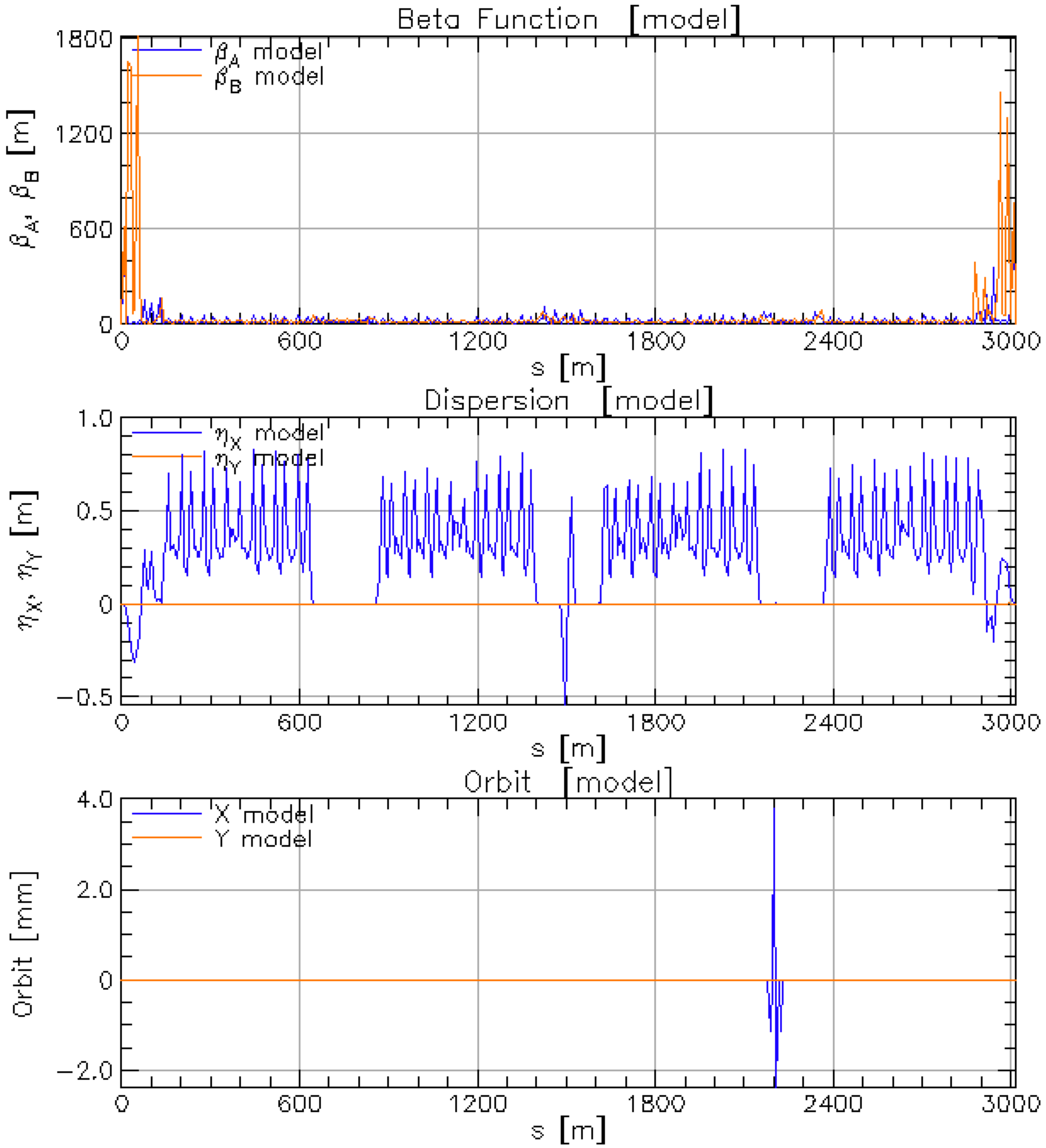
Turn: 0 10


pz vs z
1e−5
−5.5
−5.6
−5.7
−5.8
−5.9
−6.0
−6.1
pz
0.0150
0.0152
0.0154
0.0156
0.0158
0.0160
0.0162
0.0164
z

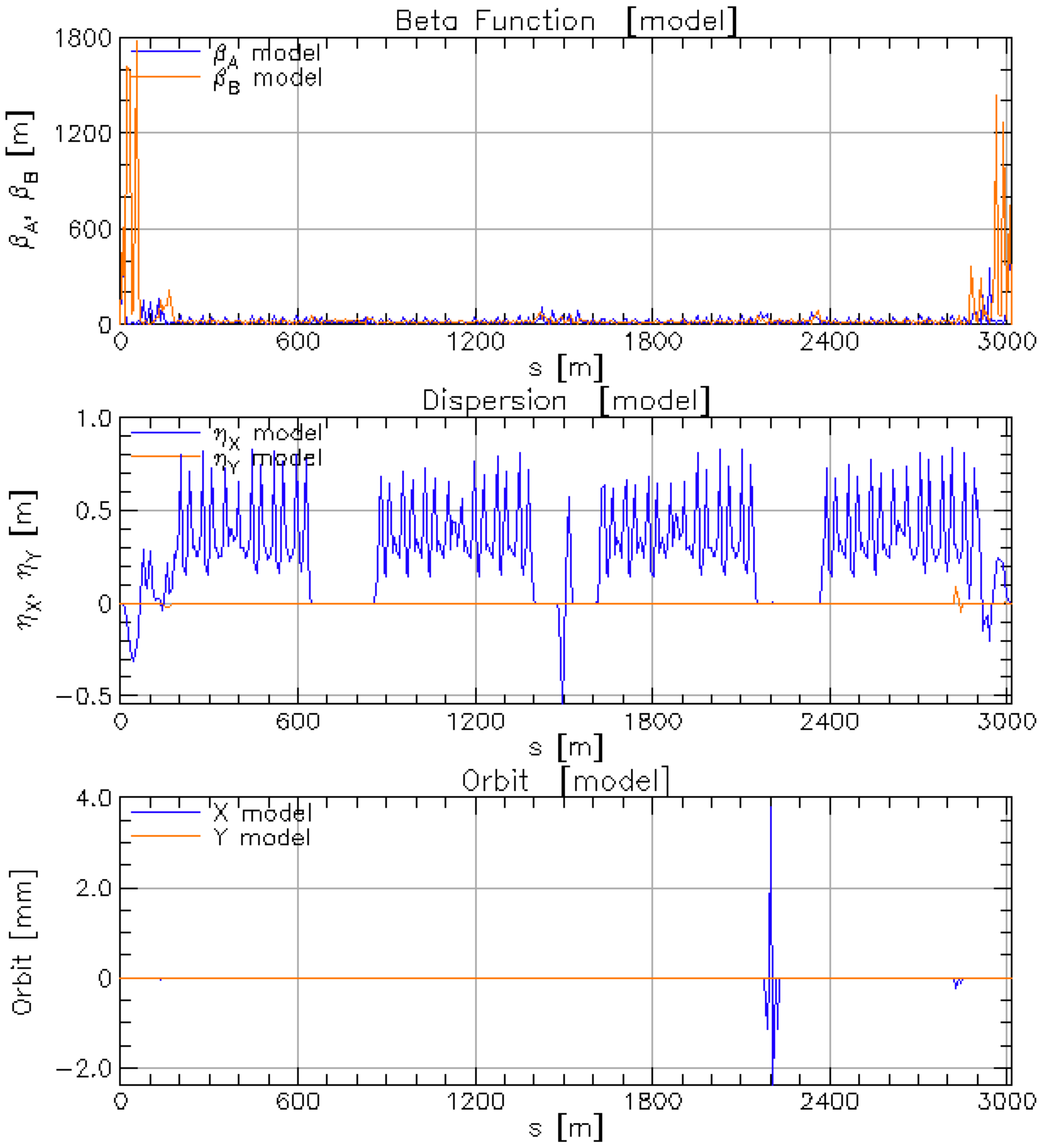

pz vs z
0.0004
0.0002
0.0000
−0.0002
−0.0004
pz
0.013
0.014
0.015
0.016
0.017
0.018
0.019
0.020
z

Turn: 0 10

Comparison of full-lattice



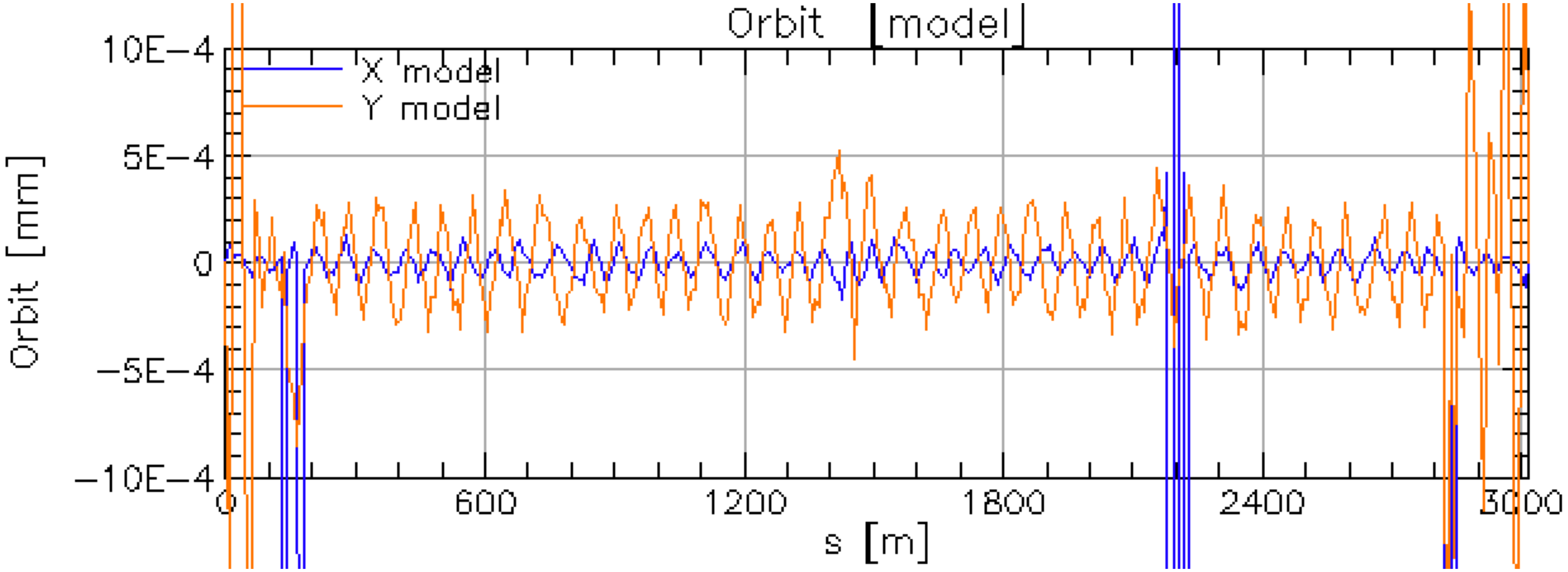
Original



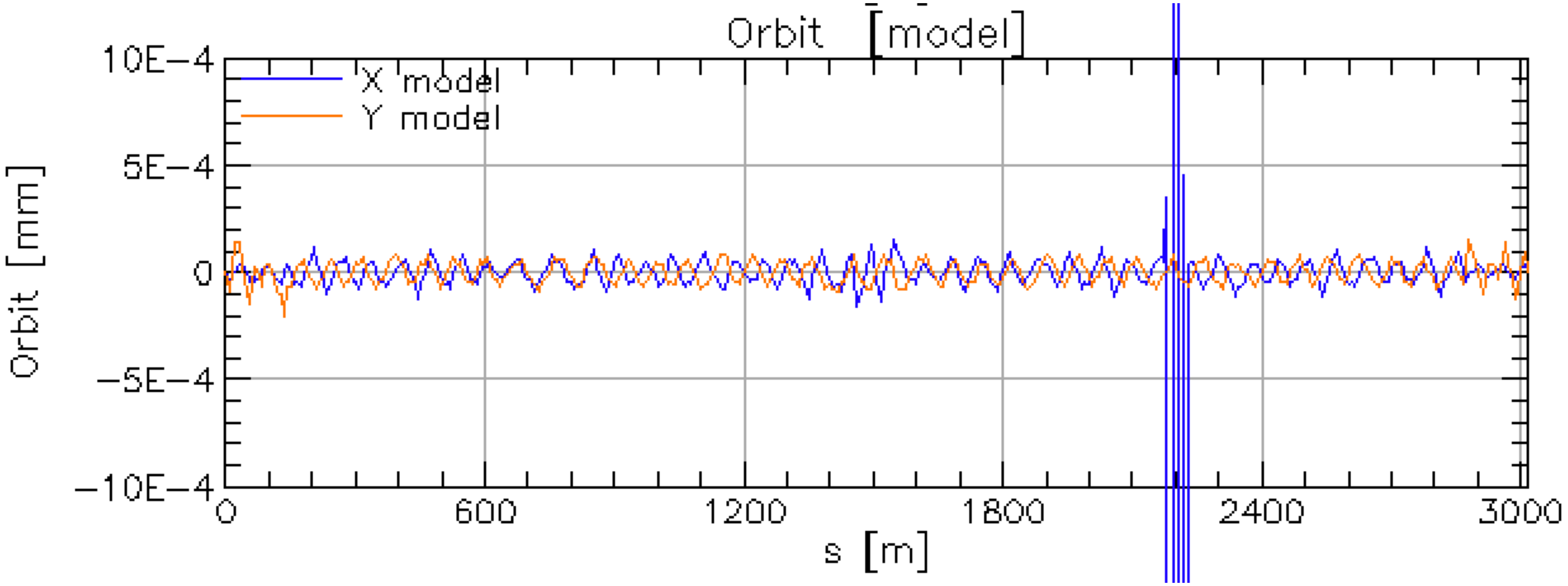
Rotator Installed

University of Victoria

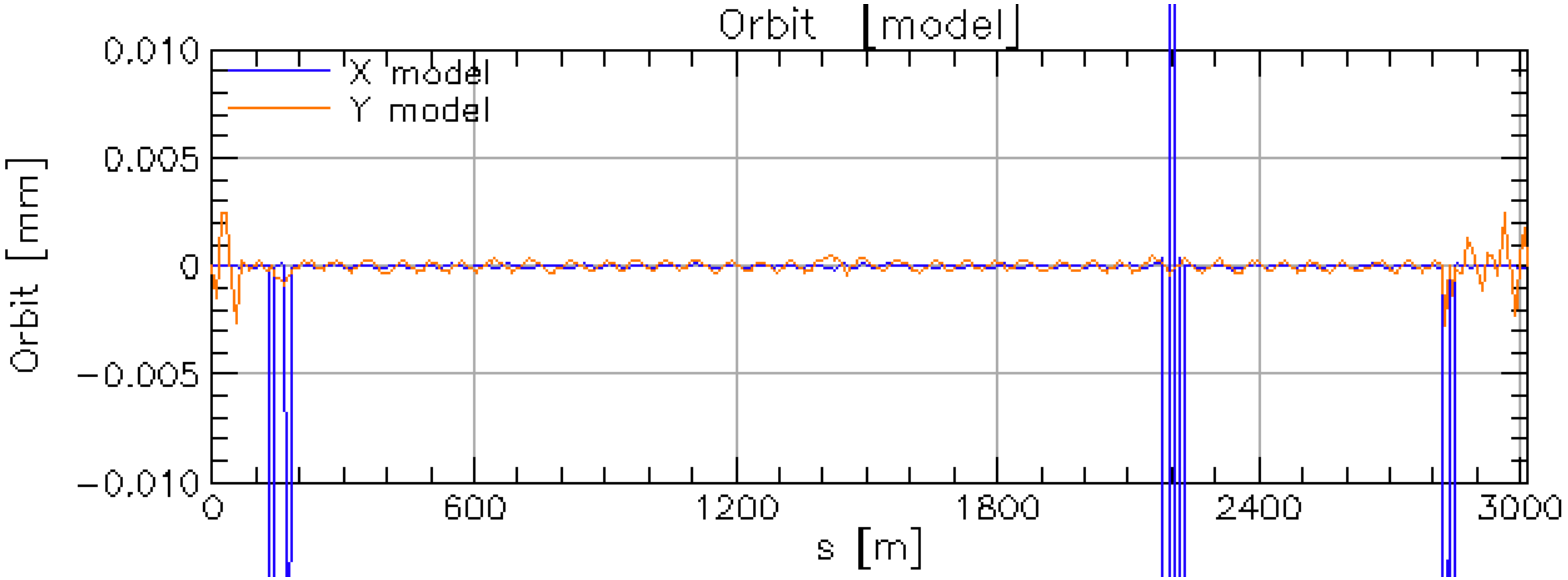
Orbit Comparison



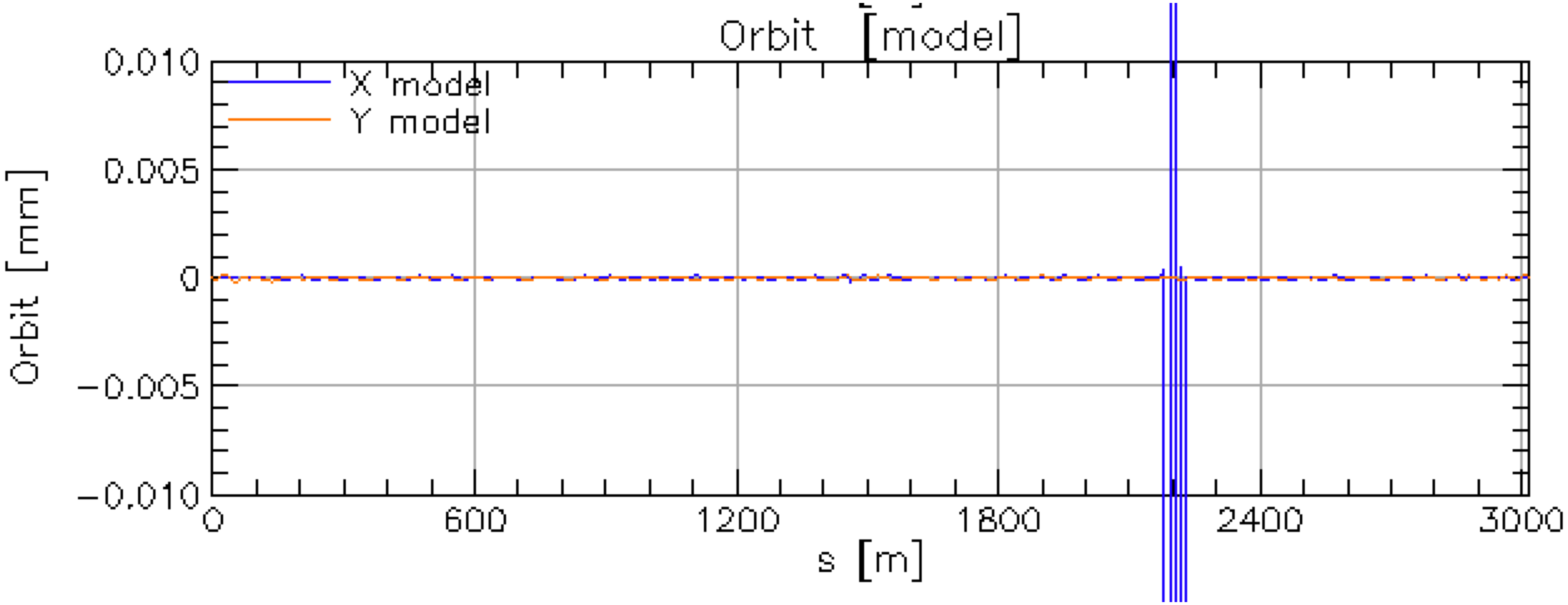
- Rot



- Original

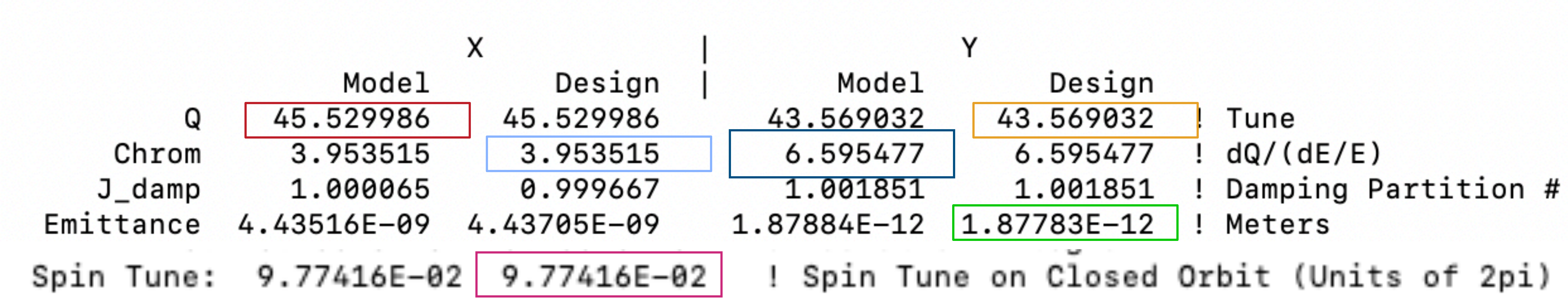


- Rot



- Original

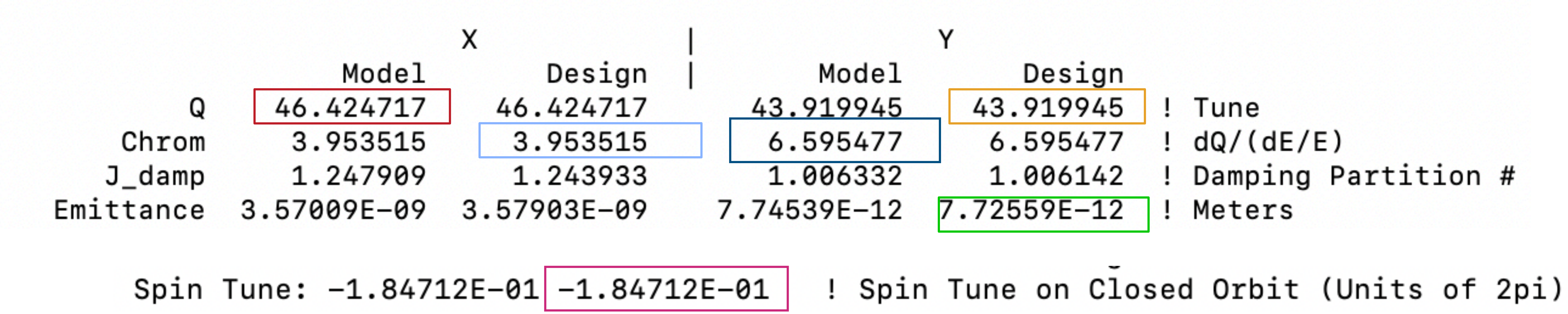
Comparison of the Ring Property After Chrom Tuning



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

Original



```
                         X                 |                  Y
                Model          Design      |         Model          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          1.006332       1.006142  ! Damping Partition #
Emittance   3.57009E-09    3.57903E-09       7.74539E-12    7.72559E-12  ! Meters
```

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

Rotator Installed

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 $K_n L \simeq \dfrac{3B_n L}{70}$

Simulation Tool

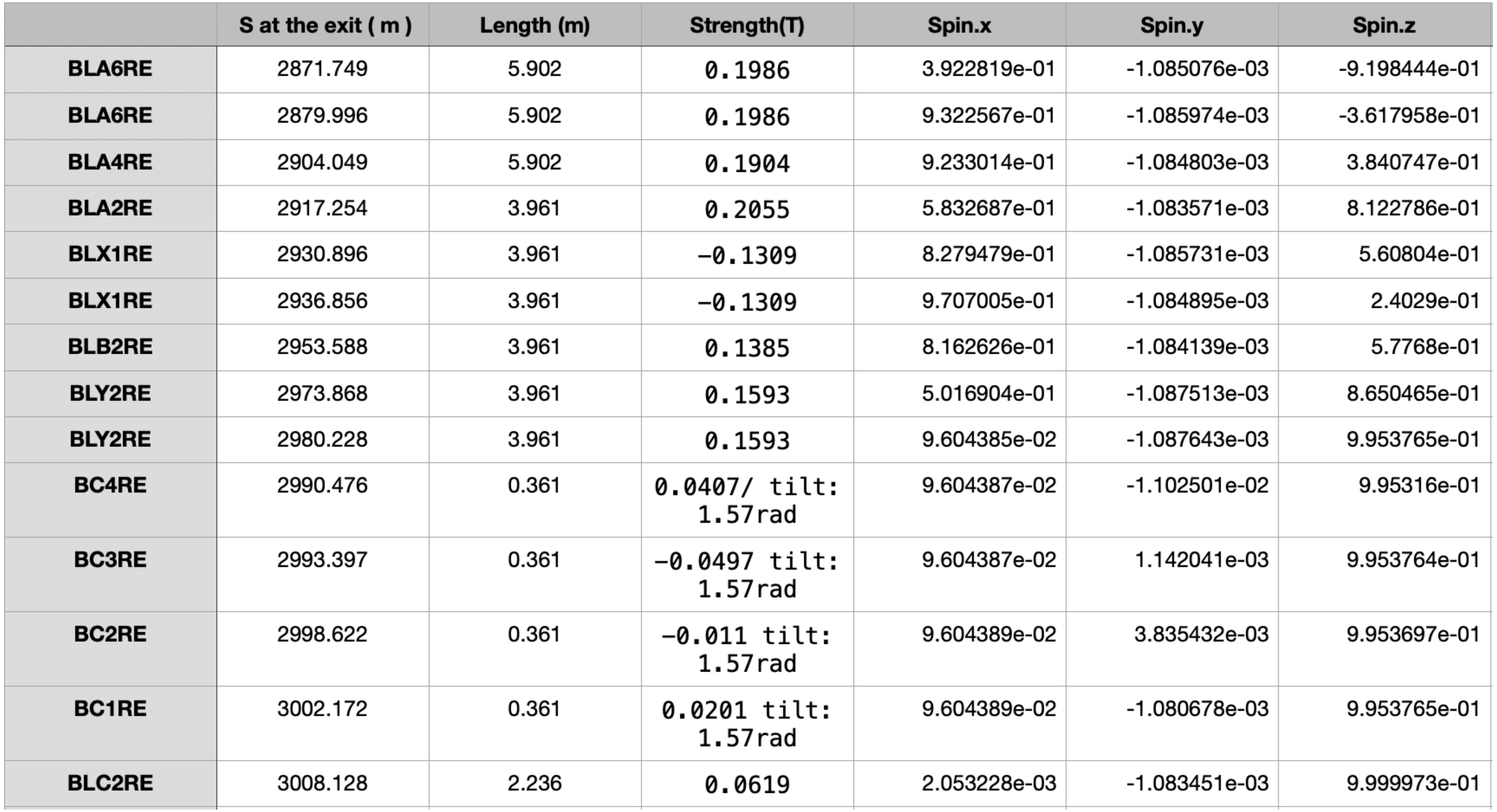
- **Bmad** is an open-source software library (aka toolkit)created/maintained by David Sagan at Cornell University for simulating charged particles and X-rays. Étienne Forest’s “Polymorphic Tracking Code” (**PTC**) is incorporated into it.

- **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

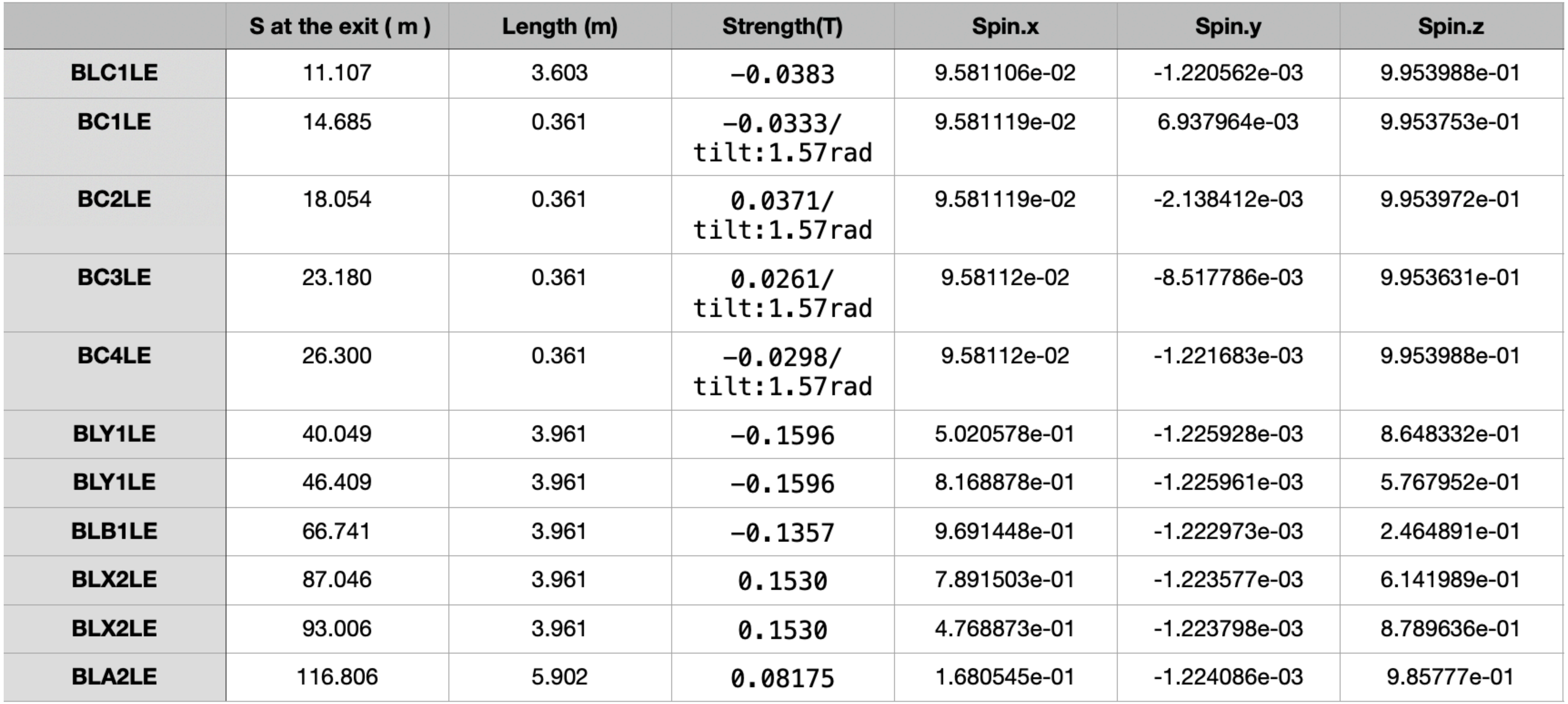
- Optimization Algorithm: LMDIF is to minimize the sum of the squares of nonlinear functions by a modification of the Levenberg-Marquardt algorithm

University of Victoria



	S at the exit (m)	Length (m)	Strength(T)	Spin.x	Spin.y	Spin.z
BLA6RE	2871.749	5.902	0.1986	3.922819e-01	-1.085076e-03	-9.198444e-01
BLA6RE	2879.996	5.902	0.1986	9.322567e-01	-1.085974e-03	-3.617958e-01
BLA4RE	2904.049	5.902	0.1904	9.233014e-01	-1.084803e-03	3.840747e-01
BLA2RE	2917.254	3.961	0.2055	5.832687e-01	-1.083571e-03	8.122786e-01
BLX1RE	2930.896	3.961	−0.1309	8.279479e-01	-1.085731e-03	5.60804e-01
BLX1RE	2936.856	3.961	−0.1309	9.707005e-01	-1.084895e-03	2.4029e-01
BLB2RE	2953.588	3.961	0.1385	8.162626e-01	-1.084139e-03	5.7768e-01
BLY2RE	2973.868	3.961	0.1593	5.016904e-01	-1.087513e-03	8.650465e-01
BLY2RE	2980.228	3.961	0.1593	9.604385e-02	-1.087643e-03	9.953765e-01
BC4RE	2990.476	0.361	0.0407/ tilt: 1.57rad	9.604387e-02	-1.102501e-02	9.95316e-01
BC3RE	2993.397	0.361	−0.0497 tilt: 1.57rad	9.604387e-02	1.142041e-03	9.953764e-01
BC2RE	2998.622	0.361	−0.011 tilt: 1.57rad	9.604389e-02	3.835432e-03	9.953697e-01
BC1RE	3002.172	0.361	0.0201 tilt: 1.57rad	9.604389e-02	-1.080678e-03	9.953765e-01
BLC2RE	3008.128	2.236	0.0619	2.053228e-03	-1.083451e-03	9.999973e-01

Table 1: Spin information at the exit of dipoles between the R-Rot and the IP



	S at the exit (m)	Length (m)	Strength(T)	Spin.x	Spin.y	Spin.z
BLC1LE	11.107	3.603	−0.0383	9.581106e-02	-1.220562e-03	9.953988e-01
BC1LE	14.685	0.361	−0.0333/ tilt:1.57rad	9.581119e-02	6.937964e-03	9.953753e-01
BC2LE	18.054	0.361	0.0371/ tilt:1.57rad	9.581119e-02	-2.138412e-03	9.953972e-01
BC3LE	23.180	0.361	0.0261/ tilt:1.57rad	9.58112e-02	-8.517786e-03	9.953631e-01
BC4LE	26.300	0.361	−0.0298/ tilt:1.57rad	9.58112e-02	-1.221683e-03	9.953988e-01
BLY1LE	40.049	3.961	−0.1596	5.020578e-01	-1.225928e-03	8.648332e-01
BLY1LE	46.409	3.961	−0.1596	8.168878e-01	-1.225961e-03	5.767952e-01
BLB1LE	66.741	3.961	−0.1357	9.691448e-01	-1.222973e-03	2.464891e-01
BLX2LE	87.046	3.961	0.1530	7.891503e-01	-1.223577e-03	6.141989e-01
BLX2LE	93.006	3.961	0.1530	4.768873e-01	-1.223798e-03	8.789636e-01
BLA2LE	116.806	5.902	0.08175	1.680545e-01	-1.224086e-03	9.85777e-01

Table 2: Spin information at the exit of dipoles between the L-Rot and the IP

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

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