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CTF3-Note-091

OPTICS DESIGN OF TRANSFER LINE-2 FOR CTF3

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Abstract

The CTF-3 (CLIC Testing Facility-3) is a project to demonstrate the concepts of high frequency RF generation for the particle acceleration using a drive electron beam. This concept of RF generation will be used in the CLIC (Compact Linear Collider), a future collider at CERN. This facility will also be useful to test some of the RF components of the CLIC. In the CTF-3, a 150 MeV electron beam extracted from the Combiner Ring will be transported to the CLEX area through the Transfer Line-2 (TL-2). RRCAT has carried out the optical design of the TL-2 under the DAE-CERN collaboration. In this report, we present the beam optical design of this transfer line. This line will be used to control the bunch length and Twiss parameters at the entrance to the CLEX area. The line will have a wide tunability of R_{56} parameter, ranging from –0.30m to +0.30m to offer a wide range control over the bunch length. This line has been designed considering the constraints imposed by the building geometry and the magnetic elements to be used. The design optimization of the line has been done up to second order for the entire R_{56} range, keeping T_{566} practically zero and emittance dilution below 10%.

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1. Introduction:

The CLIC (Compact Linear Collider) is an upcoming project at CERN. The acceleration cavity (normal conducting) for this collider will need a very high gradient at high frequency. This high frequency RF generation will be done using a drive electron beam. The CLIC Test Facility-3 (CTF3) is to demonstrate the concept behind the high frequency RF generation (at 16 GHz) with a drive beam of electrons ***[1]***. This drive beam must have a definite bunch length to achieve the high efficiency for RF generation ***[2]***. Therefore the bunch length control of the drive electron beam is essential. The Transfer Line-2 (TL-2) will transport the electron beam at nominal energy of 150 MeV (peak energy 300 MeV) from the Combiner Ring (CR) to the CLEX area (CLIC Experimental area). This transfer line will be used not only for proper transport of the beam but also to control the bunch length of the electron beam. The line is just before the TL-2' a short line, up to the CLEX area. Therefore TL-2 is the last line where finally the bunch length will be controlled before delivery of the beam to the experimental area. Keeping these points in view as well as that the CTF3 is a test facility, the TL-2 is designed in a way so that it can control the bunch length over a wide range. This line is to be housed in the existing building of the LEP pre injector. Thus there are geometrical constraints of the line. Since some magnets are already available at CERN, this line design was to be done using these magnets. With theses constraints, obtaining a wide tuning range for bunch length control, with correction up to second order, posed challenges in the design. RRCAT is involved in the optical design of this transfer line under the DAE-CERN collaboration. In this report, we present the beam optical design and optimization of this transfer line. In section-1, we outline the basic linear theory of the bunch length control. In section-2, we present the geometry of the building and layout of the line. Subsequent sections show the linear and nonlinear design studies of the line. Table-1 shows the main parameters of the transfer line.

Table-1 Parameters of TL-2

	CR extraction Reference point in CR as provided by CERN (center quadrupole Q540)	**CLEX injection** Reference point half way in wall separating CR and CLEX buildings
Maximum beam energy	300 MeV	300 MeV
Nominal beam energy	150 MeV	150 MeV
Nominal bunch charge	2.33 nC	2.33 nC
Bunch spacing	83.4 ps	83.4 ps
Train duration	140 ns	140 ns
β_H	4.23 m	<20 m in entire separation wall
α_H	2.76	not specified
ε_H (normalised, 1σ r.m.s.)	100 π mm mrad	<110 π mm mrad

β_V	7.79 m	<20 m in entire separation wall
α_V	-2.47	not specified
ε_V (normalised, 1σ r.m.s.)	100 π mm mrad	<110 π mm mrad
η	0 m	0 m
η’	0	0
ΔP/P (r.m.s.)	1%	1%
Height of beam-line above ground	1.35 m	0.85 m

2. Bunch Length and R_{56} parameter:

In a dipole magnet, particles with different momenta follow different trajectories and therefore the path lengths of these particles differ. This difference in path length leads to the difference in the time of flight of the particles from the start to end. The difference in path length due to a finite momentum spread in an electron beam is used to control the bunch length and the parameter that connects the path length difference and momentum deviation is known as R_{56} parameter* in the 6×6 linear transfer matrix.

$$\Delta l = -R_{56}\delta \qquad [1]$$

Here *l* shows the path length and δ is the relative momentum deviation. Optimization of the line is carried out using MAD 8. The control of R_{56} alone can not control the bunch length. For controlling the bunch length, initially the RF cavity generates the correlation between the time and energy and then the transfer line generates the correlation between the energy and path length with R_{56}. Thus, bunch length control is a two step process. Here we give a brief account of the bunch length control.

A small RF cavity approximated as a zero length cavity, modifies the momentum deviation δ of the particle, leaving z unchanged (z is the axis along the beam direction). Therefore we can write in the linear approximation, for such a cavity

$$z_1 = z_0 \qquad [2]$$

$$\delta_1 = R_{65} z_0 + R_{66}\delta_0 \qquad [3]$$

Here R_{ij} refers to the element of the 6×6 transfer matrix. The order of element in the transfer matrix is x, x’, y, y’, z (= ct) and δ. Subscripts 0 and 1 refer to the initial (entrance of cavity) and final (exit of cavity) condition of the particle respectively. The explicit expression of R_{65} and R_{66} can be written as ***[3]***

$$R_{65} = \frac{eV_{RF}}{E_0} k_{RF} \cos(\phi) \qquad [4]$$

* *In this report, we will use sign convention of MAD 8, i.e. a positive R_{56} means longer path length for lower energies.*

$$R_{66} = 1 - \frac{eV_{RF}}{E_0}\sin(\phi) \qquad [5]$$

Here V_{RF} is the peak voltage, k_{RF} is the wave vector ($=2\pi/\lambda$) of RF field and ϕ is the synchronous phase. E_0 is the energy of the on-momentum particle before it enters the cavity. Here the cavity field is assumed to be a sinusoid i.e. $V = V_{RF}\sin\phi$. In the above reference it differs from $\pi/2$ i.e. $V = V_{RF}\cos\phi$.

The magnetic channel following the RF cavity has an opposite effect, i.e. it leaves δ unchanged, while it modifies the time of flight *ct* (=*z*) depending on the momentum deviation. Therefore for a magnetic channel, we can write in linear approximation

$$z_2 = z_1 + R_{56}\delta \qquad [6]$$

$$\delta_2 = \delta_1 \qquad [7]$$

Here subscript 1 is used for the entrance and 2 for the exit from magnetic channel. Equation 2, 3 and 6, 7 together give the final co-ordinates of the particle after cavity and magnetic channel. The overall transfer matrix becomes

$$\begin{bmatrix} z \\ \delta \end{bmatrix}_2 = \begin{bmatrix} 1 + R_{65}R_{56} & R_{56}R_{66} \\ R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} z \\ \delta \end{bmatrix}_0 \qquad [9]$$

If $R_{66} = 1$ (i.e. no acceleration) matrix becomes symplectic. In this case

$$z_2 = (1 + R_{65}R_{56})z_0 + R_{56}\delta_0 \qquad [10]$$

$$\delta_2 = R_{65}z_0 + \delta_0 \qquad [11]$$

Here it is now clear, with an RF, the proper sign of R_{56} will control the bunch length. In a dipole magnet R_{56} is given by

$$R_{56} = \int \frac{\eta ds}{\rho} \qquad [12]$$

Here η is the dispersion function and ρ is the radius of curvature. The parameter R_{56} can be changed by changing dispersion function and its derivative inside the dipole magnet.

3. Building Geometry and Layout of the Line:

Figure-1 shows a schematic diagram of the CTF3. The line that connects the extraction point of the CR to the CLEX area is TL-2. Figure-2 shows the layout of the TL-2 within existing LEP pre-injector building. The geometry of the TL-2 was mainly constrained by the pre-injector building geometry. Making use of the already available magnets also posed a constraint on the design. Table-2 lists the magnets used in TL-2. The LEP pre-injector building floor is 50 cm higher than the floor of the CLEX building hence a vertical achromat is also included in the line to send the beam 50cm downwards. There is also an emergency exit and from safety point of view, no optical element has been kept in the vicinity to prevent an easy access to this exit. Besides, the line has sufficient space for placing the diagnostic devices, correction coils, vacuum ports and bellows etc.

Table-2 Magnet Parameters for TL-2

Magnet	Type	Strength/ Bending angle	Effective Length (mm)	Mechanical Length (with coils) (mm)	Mechanical width (mm)	Aperture (full) (mm)
Dipole	Short	6°-17.5°	268	520	794	100×45
	Long	12°-35°	518	770	794	100×45
	Sector	6°	470	597	276	70
Quadrupole	Slim	8.0 T/m	300	384	340	100
	Standard	5.4 T/m	380	592	819	184
	TSL	10.6 T/m	295	430	650	101
	Q3L	11.2 T/m	226	287	282	58
Sextupole	Short	180 T/m^2	100	160	420	108
	Long	44 T/m^2	246	350	420	167

Magnet utilization and power supplies in TL-2 are given in the Table-3

Table-3 Magnets and Power Supplies in TL-2

Module	Dipoles		Quadrupoles		Sextupoles	
	Magnets	Power Supplies	Magnets	Power Supplies	Magnets	Power Supplies
Module-1	1	1	3	3	----	----
Module-2	2	1	11	10	----	----
Module-3	4	2	11	7	4	2
Total	7	4	25	20	4	2

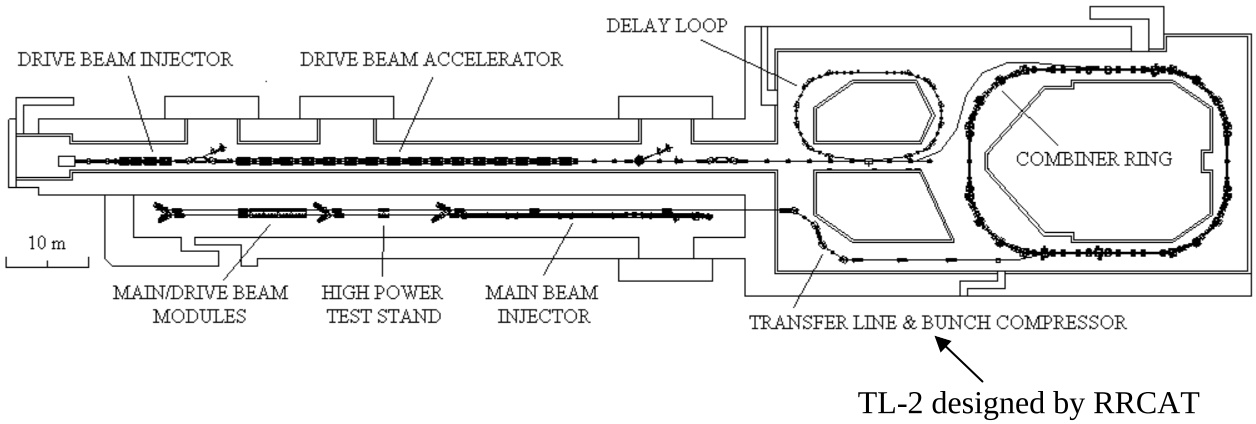


Figure-1: Schematic layout of CTF3

4. Linear Studies:

We adopted a modular approach for the design of this line. There are three Modules.

Module-1: The first Module is a horizontal achromat, formed by the two extraction septa and first horizontal dipole magnet. The bending angle of the septa and of this first dipole magnet is in opposite direction and has a magnitude of 11°. Therefore a full wavelength of dispersion function is necessary to form an achromat and at least two horizontal focusing quadrupoles are essential. This achromat is constructed using three quadrupoles, two forming achromatic condition in the horizontal plane and third one is for controlling the vertical beta function. The location of the first quadrupole has been decided so that it is sufficiently away from the Combiner Ring elements to prevent any mechanical interference with them. The second and third quadrupoles are placed at the optimal locations, to get desired Twiss parameters. Figure-3 given below is the schematic drawing (not to scale) of Module-1.

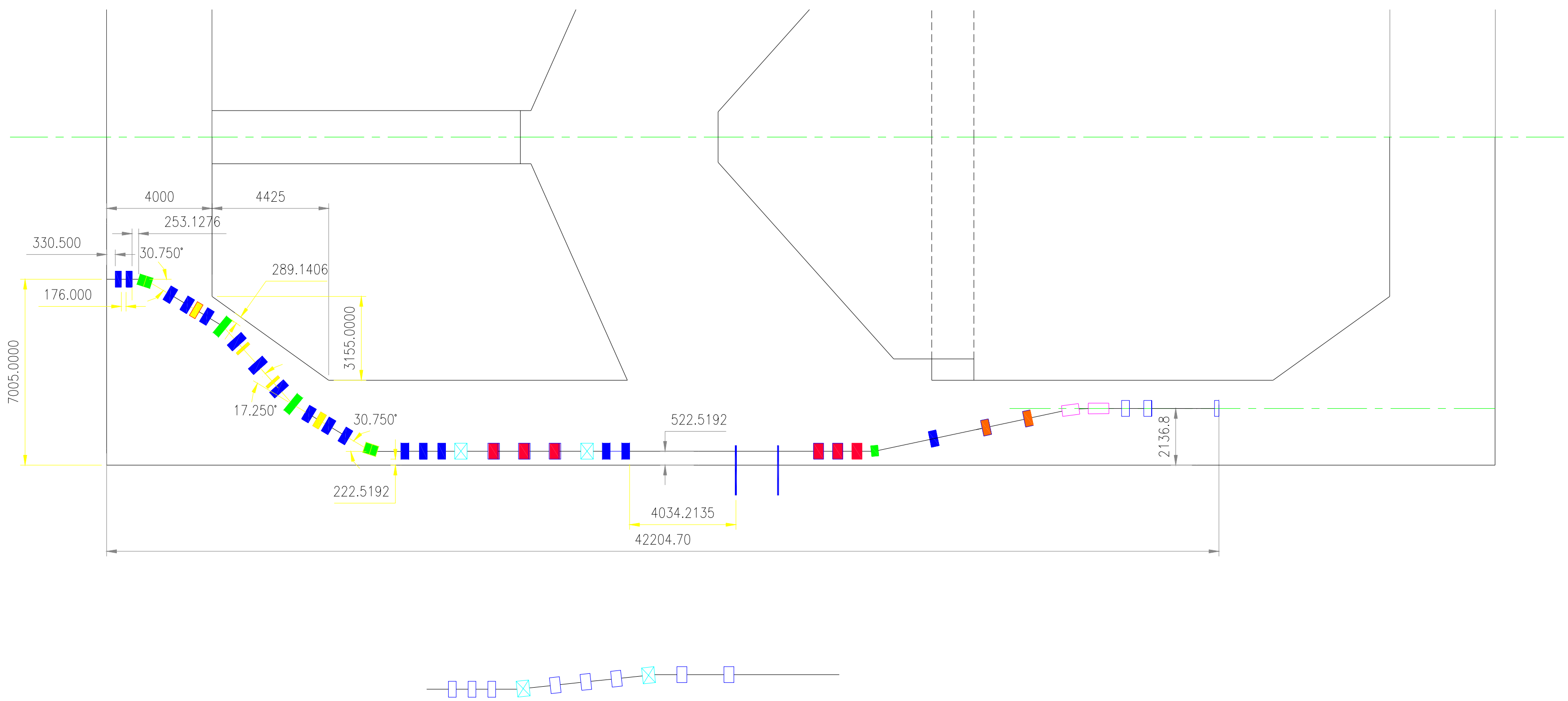


Figure-2: Layout of the TL-2 with building

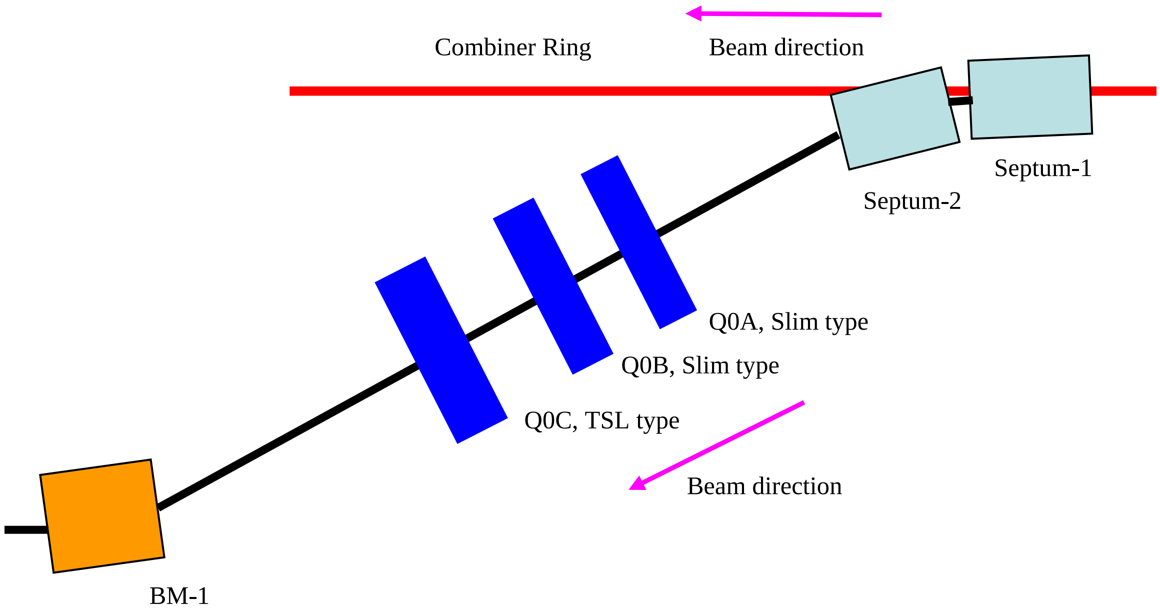


Figure-3: Schematic drawing of Module-1 (Not to scale)

4.2 Module-2: The second Module provides proper matching between the Module-1 and Module-3. It also consists of a nearly 6m clear space in which 4m space will be used for accommodating the tail clippers as shown the figure-4 and it also has a vertical achromat to send the beam 50cm downwards. This achromat is formed with two 6° sector dipole magnets, bending the beam in opposite direction. There is a quadrupole triplet just after the Module-1 and before the clear space. After this clear space and before the vertical achromat, there is a quadrupole doublet and after the vertical achromat and before the Module-3, there is a quadrupole triplet. On making the Module-2 free from dispersion, the value of R_{56} in the line will not be disturbed during Twiss parameter adjustment. Figure-4 shows the Module-2.

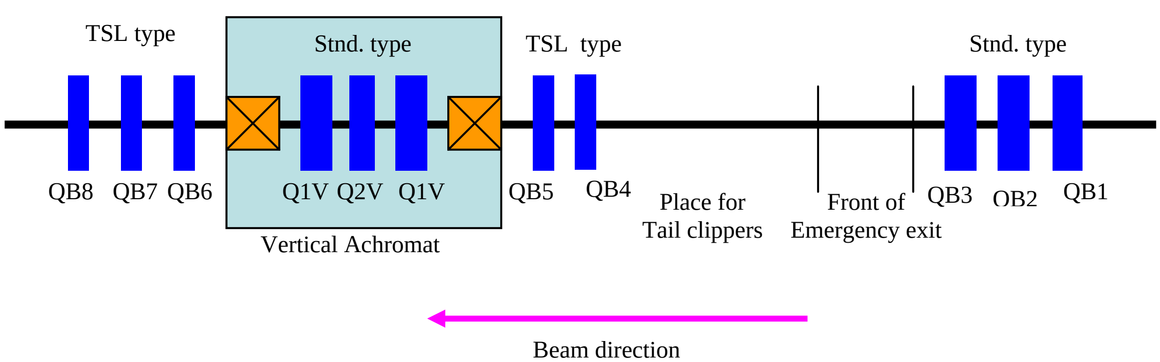


Figure-4: Schematic drawing of Module-2 (Not to scale)

4.3 Module-3: Module-3 consists of an R_{56} tunable arc and a final matching quadrupole doublet. The tunable R_{56} arc is achromatic in the entire tuning range. For making a tunable R_{56} achromatic arc, at least three dipole magnets are required to control the R_{56} parameter ***[4]***. In this, the first and last dipole magnets give fixed contributions to R_{56}, while middle magnet is used to provide the required tuning. In this line, four dipole magnets are used to form a wide tunable arc and to maintain a symmetric dispersion function. The first and fourth dipole magnets will be driven by one power supply and second and third magnet with another power supply. There is a quadrupole triplet in between the first and second dipole magnet, to obtain the required η and η' at the entrance of the second dipole magnet and required η at the location of the sextupoles, which correct T_{566} (element of the second order transfer matrix). There is second quadrupole triplet between the second and third dipole magnet with a vertical focusing quadrupole at the symmetry location. This quadrupole triplet has been used to make zero dispersion at the symmetry point. With these conditions, the adjustment of Twiss parameters in the arc became difficult and desired Twiss parameters distribution will be obtained by selecting proper values of Twiss parameters at the entrance of Module-3. After this arc, there is a quadrupole doublet, which ensures the beta functions lower than 20m at the separation wall of LEP pre injector building and CLEX area. The schematic layout of this module is shown in figure-5. The optimization of this line has been done using the computer code MAD-8, which requires guess values for starting the optimization. For obtaining these values, a separate optimization program was written in the MATLAB. The line has been optimized in such a way that in entire tuning range of R_{56}, the beta function in both the planes are less than 40m throughout the line. Dispersion is maintained up to ~2m for controlling T_{566} with sextupoles within the specified strength. The beam sizes up to 3σ are well within the aperture.

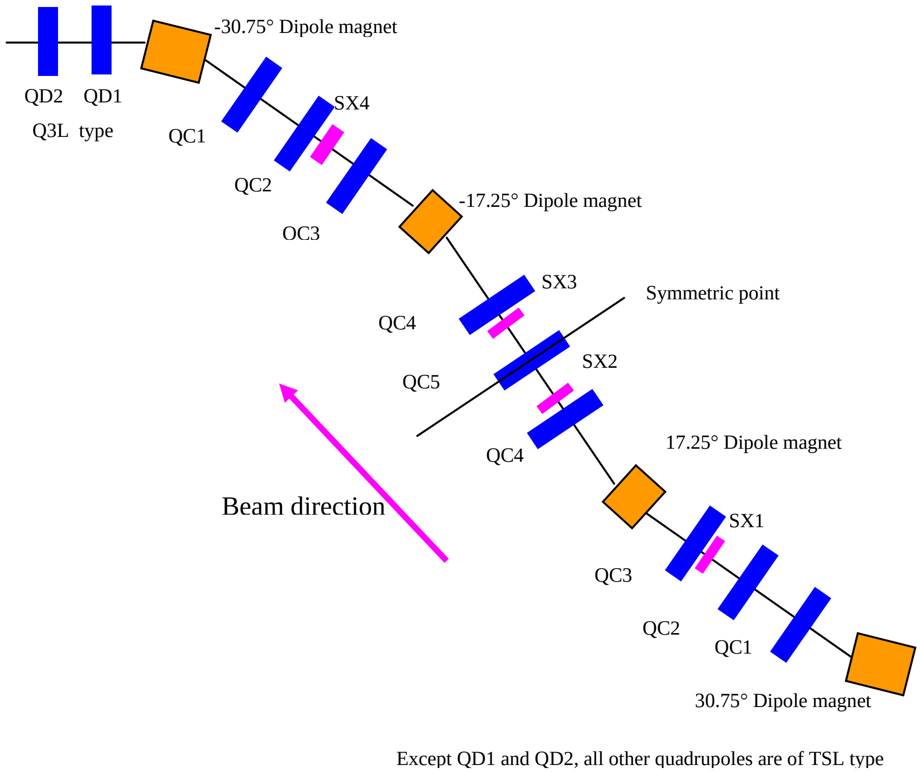


Figure-5: Schematic drawing of Module-3 (Not to scale)

The aperture of vacuum chamber is not the same everywhere in the line. The vacuum chamber dimension in the line in different section is given in the table-4.

Table-4 Aperture of Vacuum Chambers in TL-2

Module	Type of chamber	Aperture full (mm)
Module-1	Racetrack	90×40
Module-2	Round	40
Module-3	Racetrack	90×40

The rms beam sizes up to $n\sigma$ in a line is given by $\sqrt{n^2\varepsilon\beta + (\eta\delta)^2}$; where $\varepsilon = \frac{\varepsilon_{normalized}}{\gamma\beta}$.

In the expression of emittance, γ and β are the relativistic parameters. By taking normalized emittance 100π mm-mrad for 1σ, the beam sizes in the dispersion free region up to the 3σ (at 150 MeV, considering beta function 40m) will be 10.95mm and with 1% momentum offset, the rms beam size with almost 2.5m dispersion function (in horizontal plane in Module-3) will be 25.06mm. Figure-6 show the optical parameters of the TL-2 at different settings of R_{56} and figure-7 show the beam size for 1% momentum offset at R_{56} = -0.30m, 0.00m and +0.30m. Table-5 shows the quadrupole settings for the different R_{56} tuning.

Table-5 (A) Quadrupole strengths (m^{-2}) for Negative and Zero (isochronous mode) R_{56}

Quadrupole & Type	R_{56} (m)						
	-0.30	-0.25	-0.20	-0.15	-0.10	-0.05	0.00
Q0A [Slim]	5.499300						
Q0B [Slim]	-4.889800						
Q0C [TSL]	4.528500						
QB1 [Standard]	3.874428						
QB2 [Standard]	-2.947592						
QB3 [Standard]	0.6759084						
QB4 [TSL]	3.656300	3.602400	3.723600	3.745300	3.736400	3.721600	3.686929
QB5 [TSL]	-6.018900	-5.772700	-6.001800	-6.152800	-6.082400	-6.077500	-6.115232
Q1V [Standard]	-4.93990						
Q2V [Standard]	3.24745						
QB6 [TSL]	-1.631300	-2.239000	-0.091000	-0.059200	-0.000200	-0.425200	-0.055980
QB7 [TSL]	3.526200	4.962300	3.783300	4.010000	3.923400	4.237600	3.941288
QB8 [TSL]	-0.844800	-3.856800	-3.778200	-4.570700	-4.507300	-4.690100	-4.403360
QC1 [TSL]	4.392000	Off	0.520900	1.591602	1.594800	1.635900	2.002300
QC2 [TSL]	-6.309200	-8.147613	-8.127300	-7.165900	-7.273400	-7.180000	-7.616500
QC3 [TSL]	5.092700	7.667834	7.730600	7.441400	7.635000	7.771300	8.015500
QC4 [TSL]	0.004100	9.104372	8.721900	8.569588	8.101671	7.741651	7.436591
QC5 [TSL]	-2.358400	-5.018986	-4.786600	-4.665504	-4.627374	-4.523026	-4.639579
QD1 [Q3L]	-4.552400	-6.750623	-8.082500	-8.945800	-8.904300	-10.121200	-7.861000
QD2 [Q3L]	-5.606900	6.926099	8.061600	7.141900	7.064500	7.993200	7.181300

Table-5 (B) Quadrupole strengths (m^{-2}) for Positive R_{56} settings

Quadrupole & Type	R_{56} (m)					
	0.05	0.10	0.15	0.20	0.25	0.30
Q0A [Slim]	5.49930					
Q0B [Slim]	-4.88980					
Q0C [TSL]	4.52850					
QB1 [Standard]	3.874428					
QB2 [Standard]	-2.947592					
QB3 [Standard]	0.6759084					
QB4 [TSL]	3.694465	3.709042	3.720976	3.686929	3.720538	3.71460
QB5 [TSL]	-5.940875	-6.000374	-5.994994	-6.115232	-6.117621	-6.29940
Q1V [Standard]	-4.93990					
Q2V [Standard]	3.24745					
QB6 [TSL]	-0.6103124	-0.3429193	Off	Off	-0.6947597	-0.000400
QB7 [TSL]	4.297115	4.116014	3.886963	3.755000	4.301927	3.904900
QB8 [TSL]	-4.268515	-4.308398	-4.334767	-4.273200	-4.364285	-5.064100
QC1 [TSL]	1.989700	2.153567	2.813288	3.189962	4.8462	5.009872
QC2 [TSL]	-7.934264	-7.924808	-8.037459	-8.089192	-8.504432	-8.401705
QC3 [TSL]	8.262446	8.429037	8.642021	8.881988	9.531533	9.964513
QC4 [TSL]	7.217666	7.000154	6.723196	6.504467	5.943693	5.789055
QC5 [TSL]	-4.468653	-4.521916	-4.288874	-4.229013	-4.088262	-4.053587
QD1 [Q3L]	-7.043518	-7.452513	-8.136665	-8.883000	-8.290177	-10.57458
QD2 [Q3L]	5.803209	6.259339	6.520035	8.436400	6.754256	8.581195

* In these tables (and in the entire report), the negative sign in front of the quadrupole strength (and sextupole strength) shows the defocusing nature of magnet in horizontal plane.

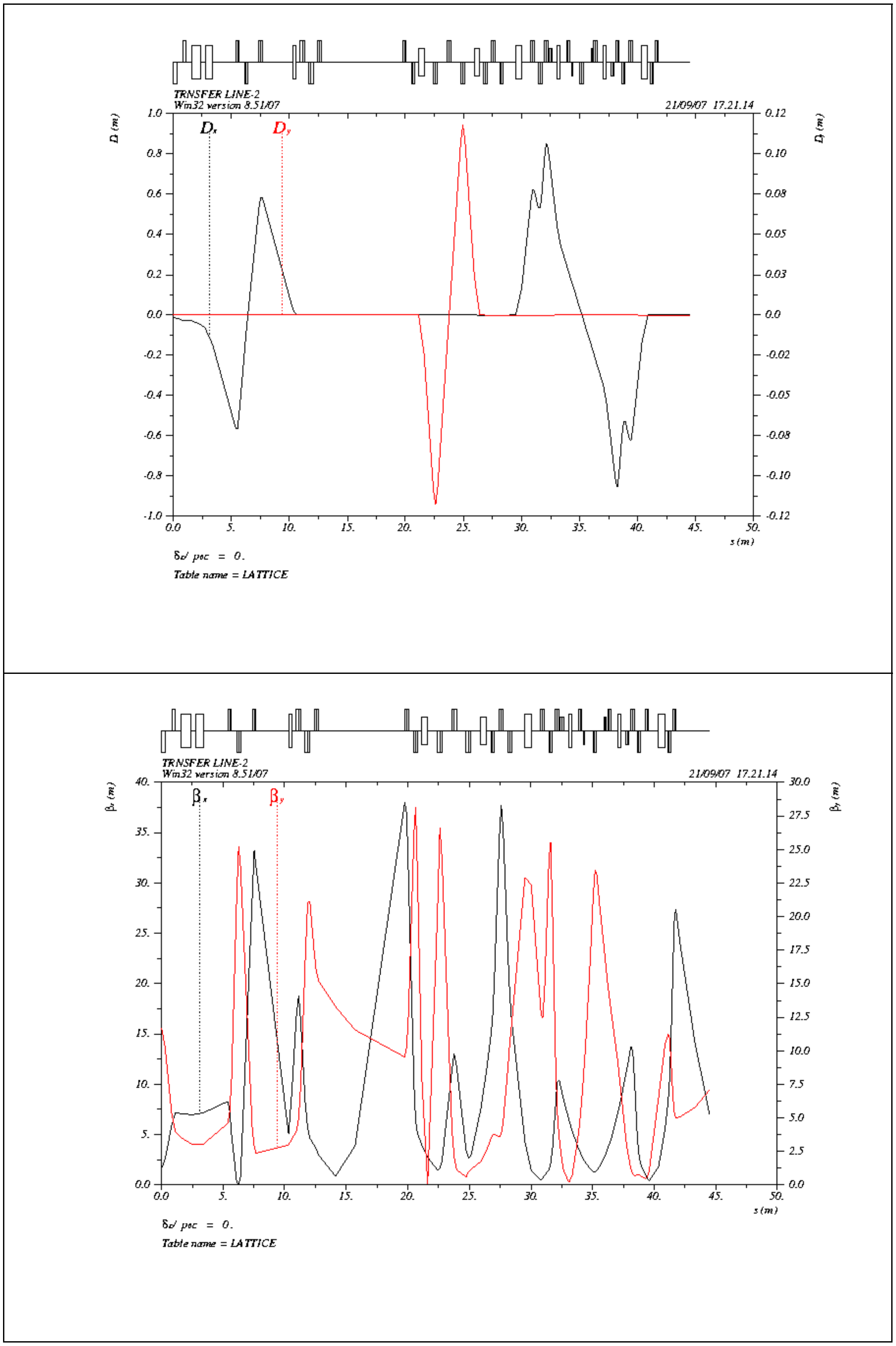
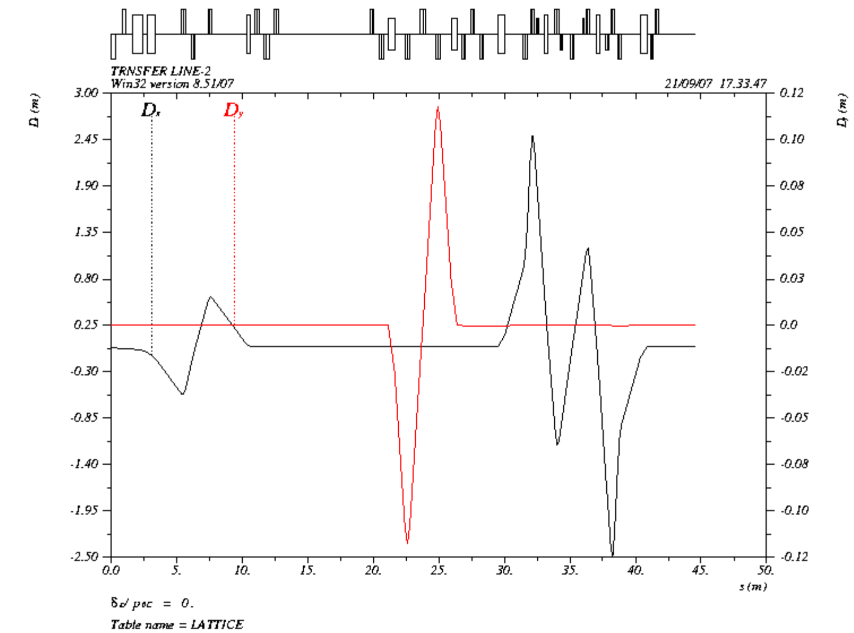


Figure-6A: Dispersion and beta functions @ R_{56} = -0.30m



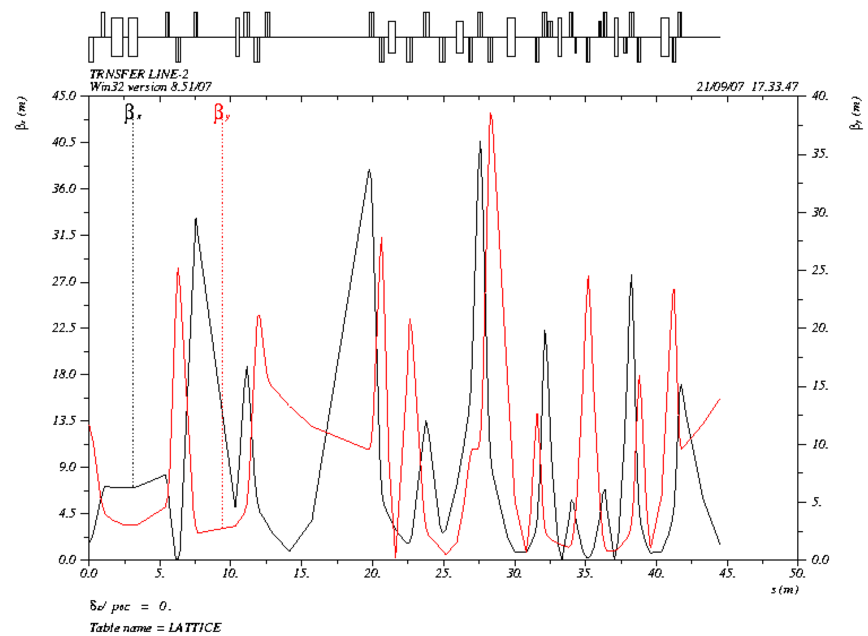


Figure-6B: Dispersion and beta functions @ R_{56} = -0.25m

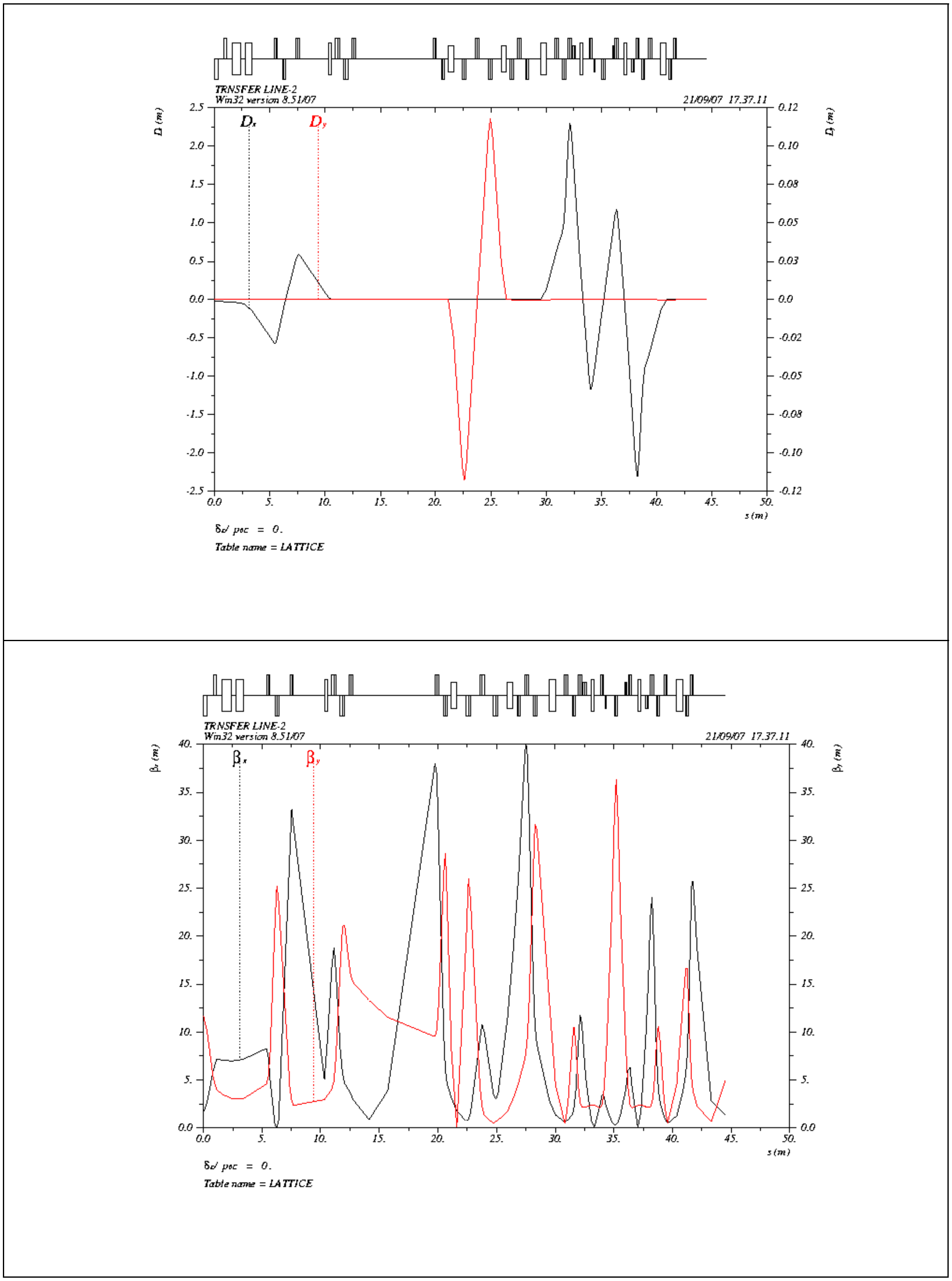


Figure-6C: Dispersion and beta functions @ R_{56} = -0.20m

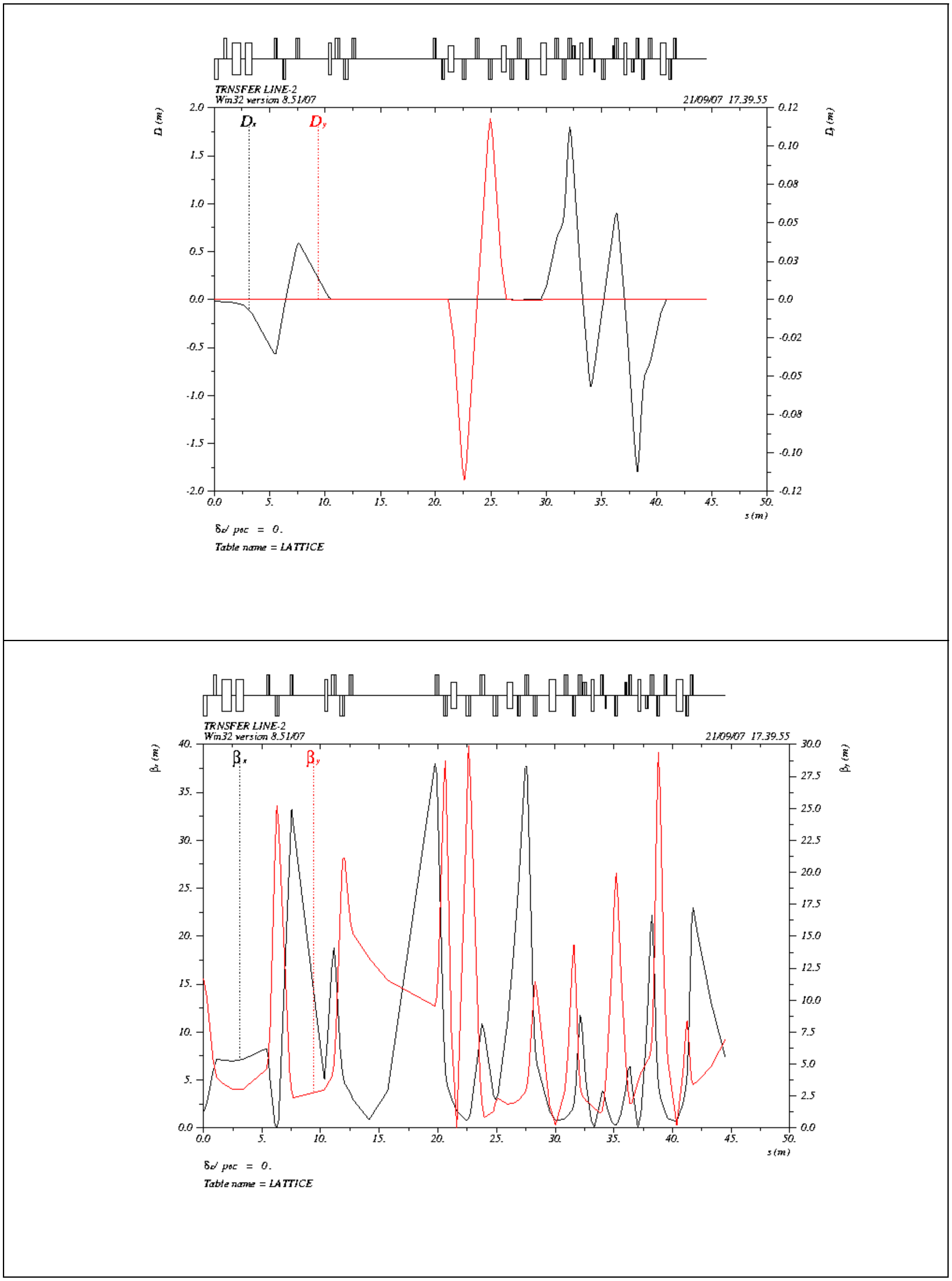
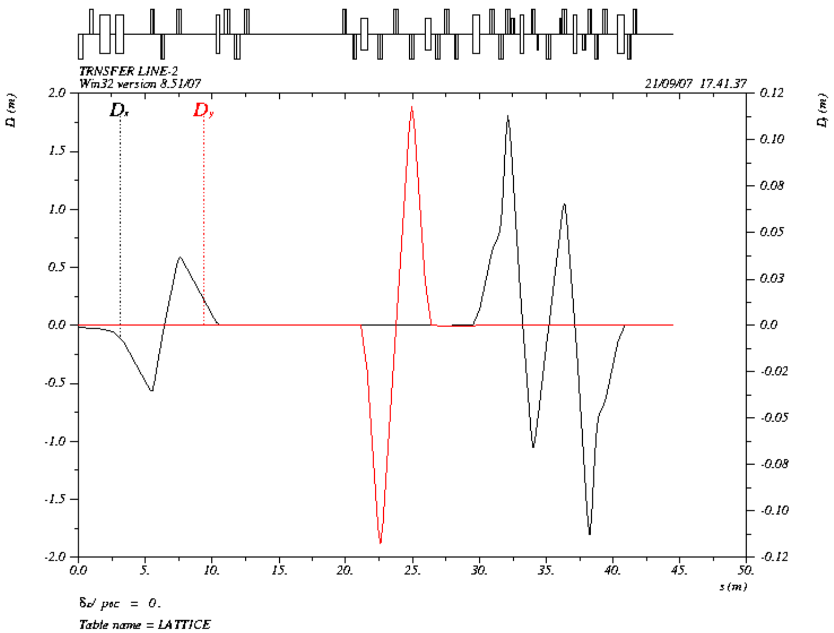


Figure-6D: Dispersion and beta functions @ R_{56} = -0.15m



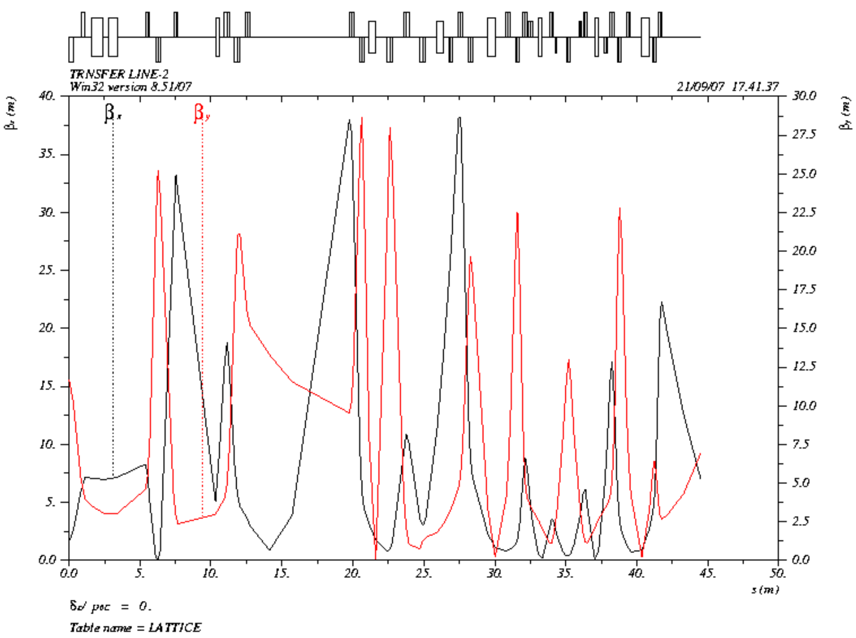


Figure-6E: Dispersion and beta functions @ R_{56} = -0.10m

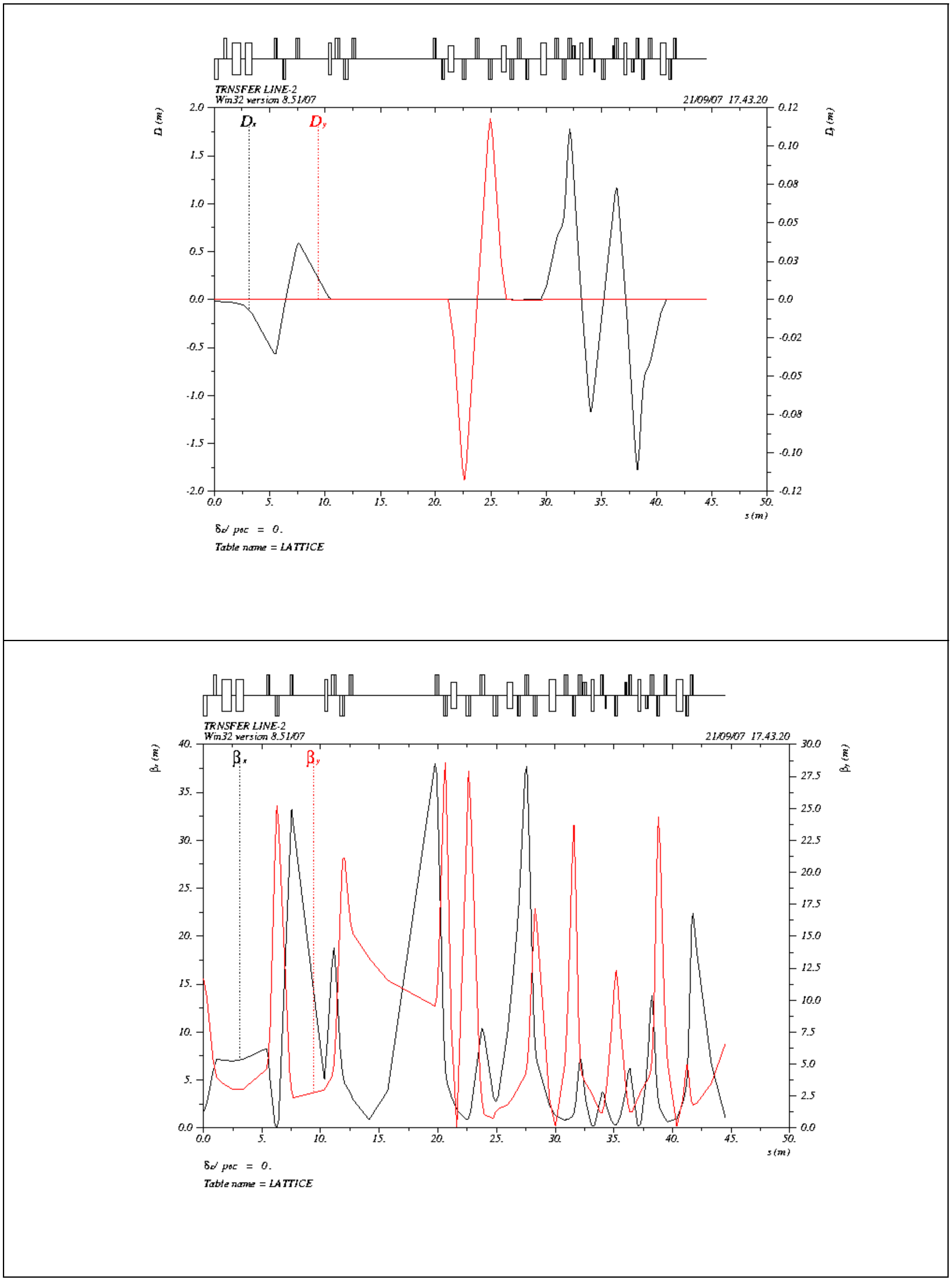
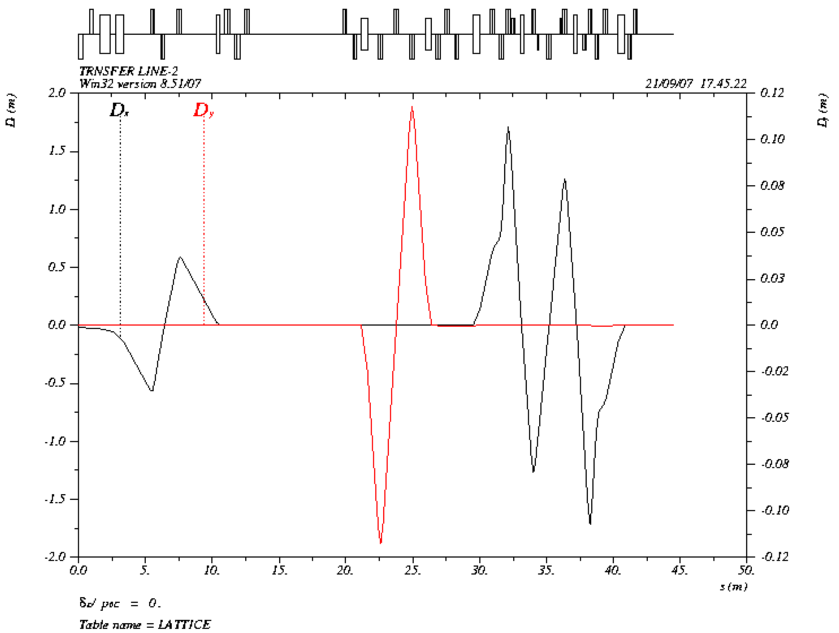


Figure-6F: Dispersion and beta functions @ R_{56} = -0.05m



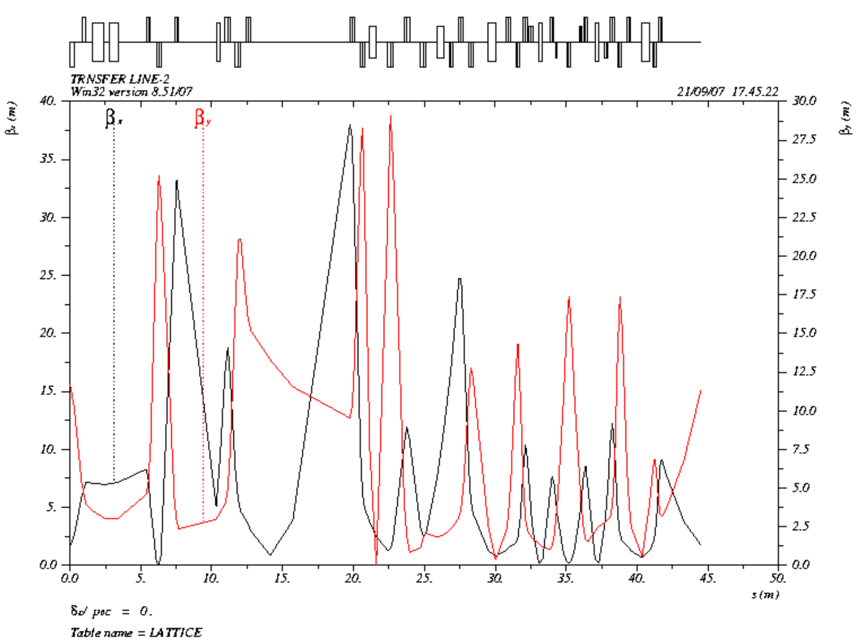
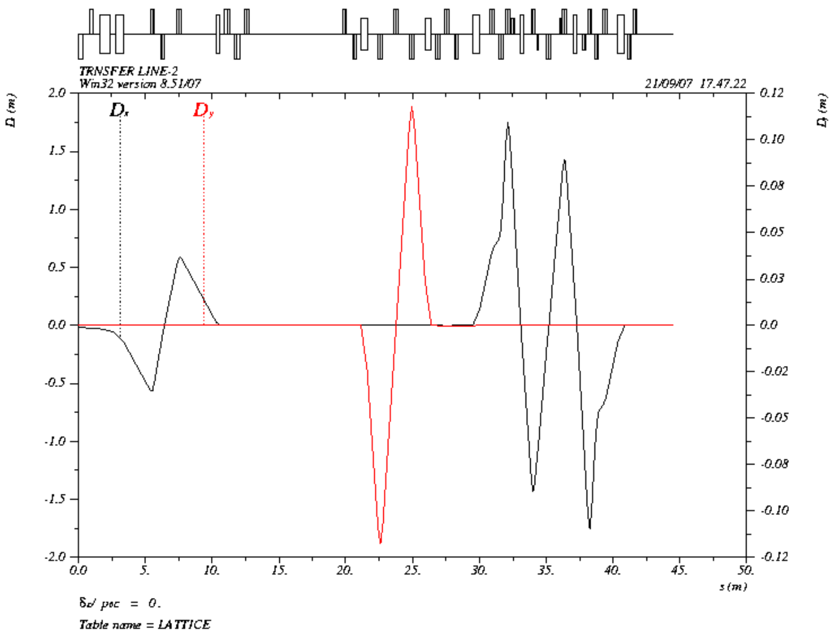


Figure-6G: Dispersion and beta functions @ R_{56} = 0.00m



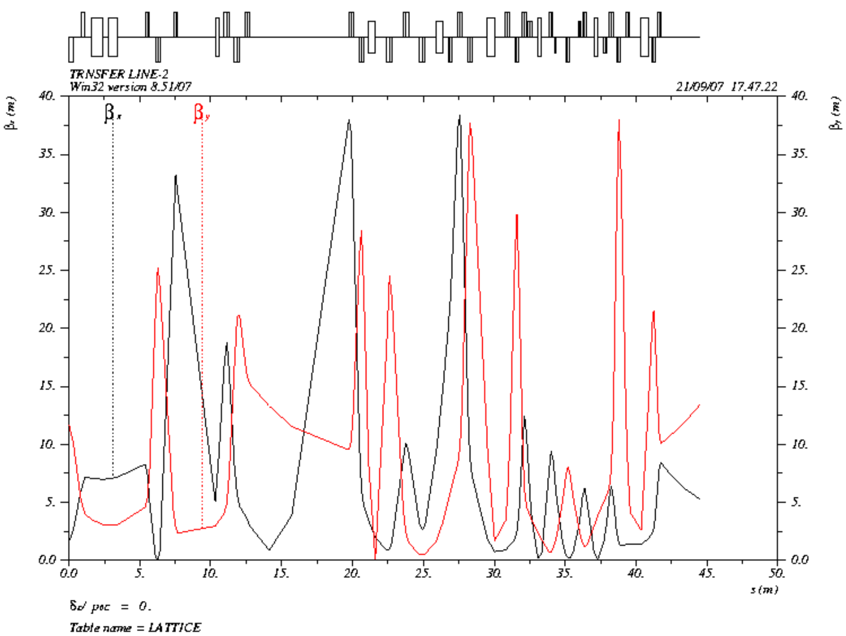
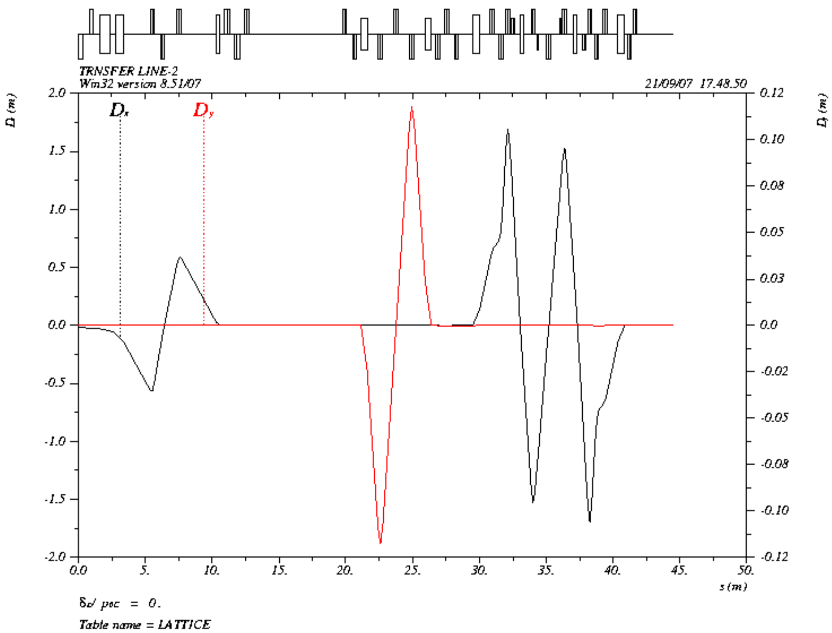


Figure-6H: Dispersion and beta functions @ R_{56} = +0.05m



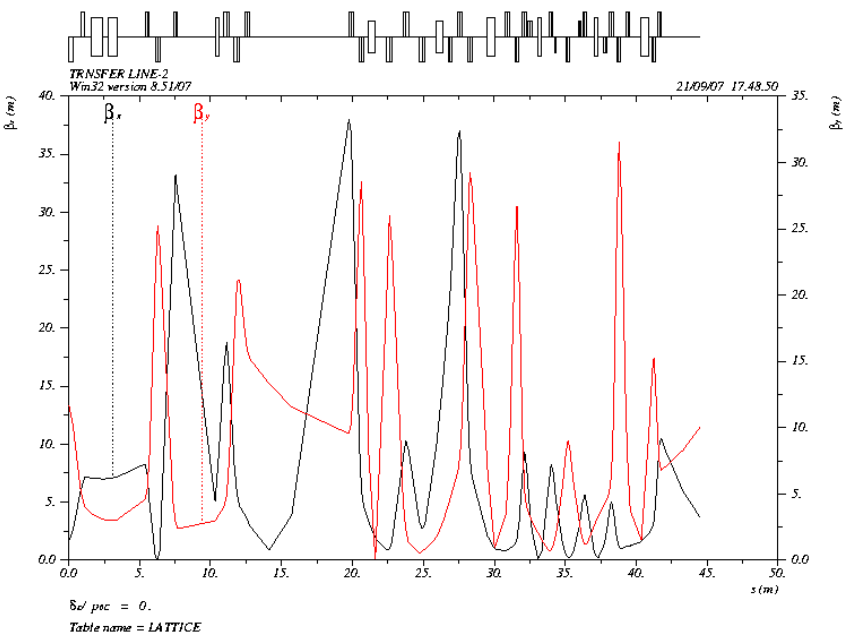


Figure-6I: Dispersion and beta functions @ R_{56} = +0.10m

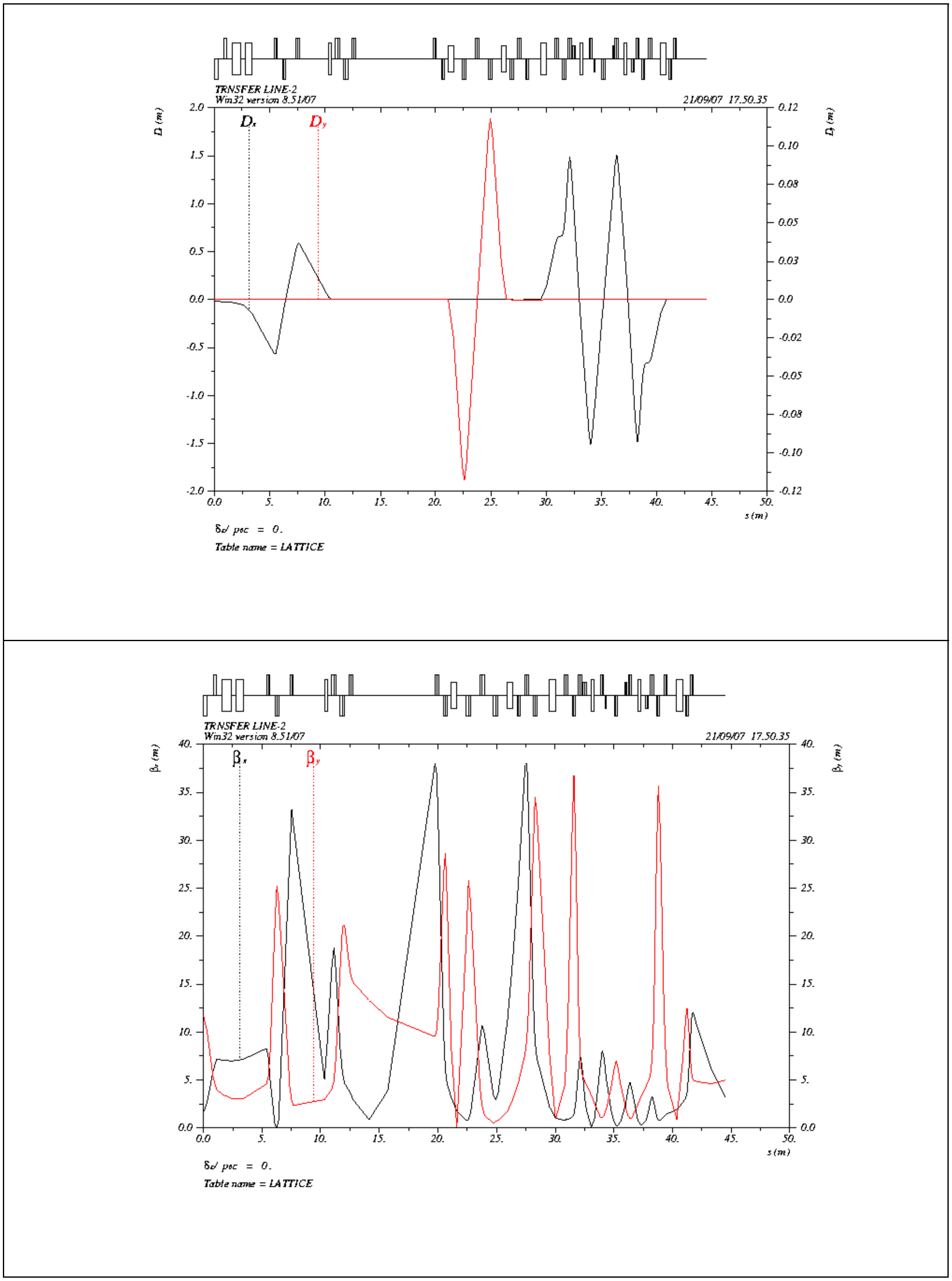


Figure-6J: Dispersion and beta functions @ R_{56} = +0.15m

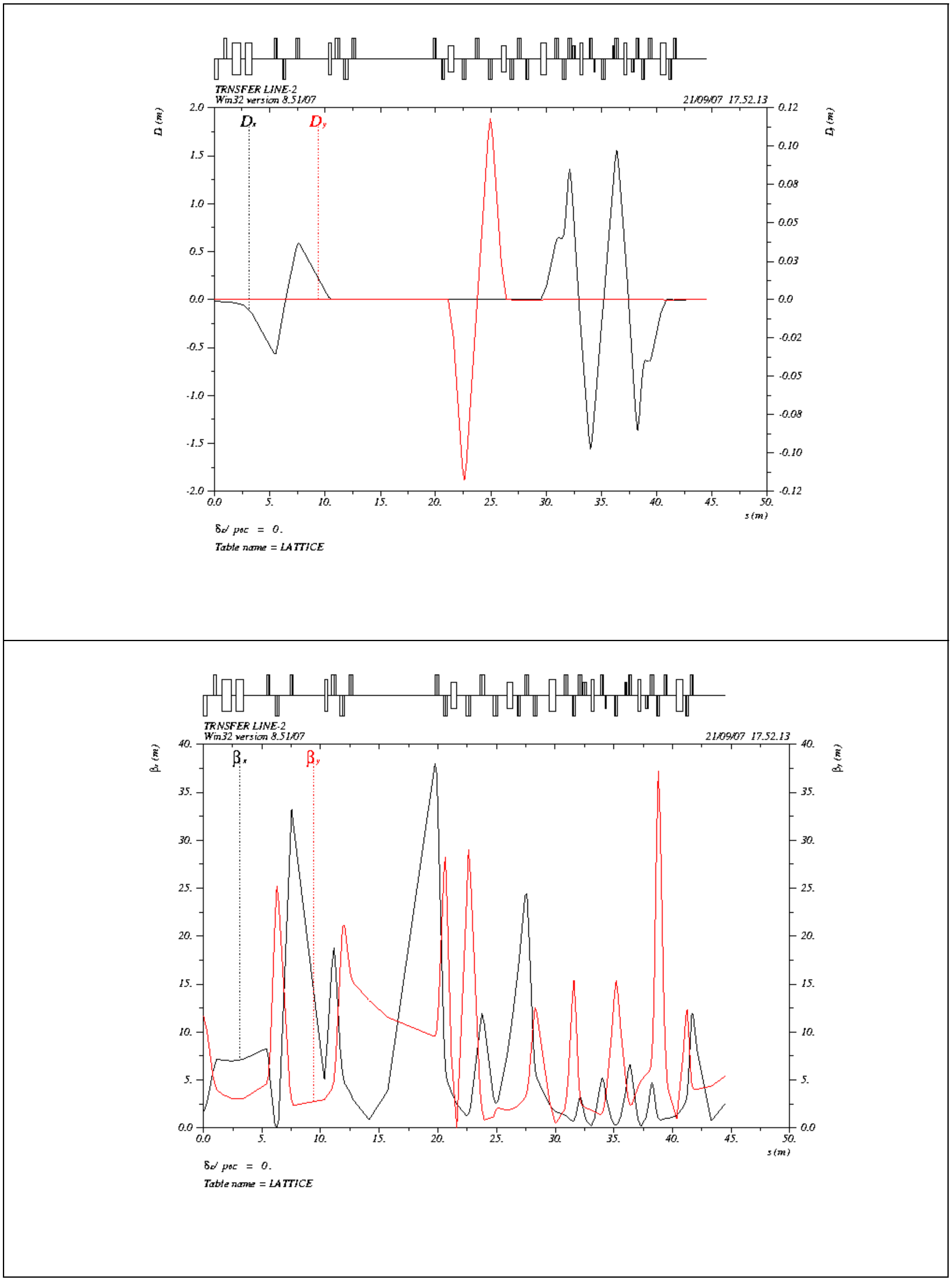


Figure-6K: Dispersion and beta functions @ R_{56} = +0.20m

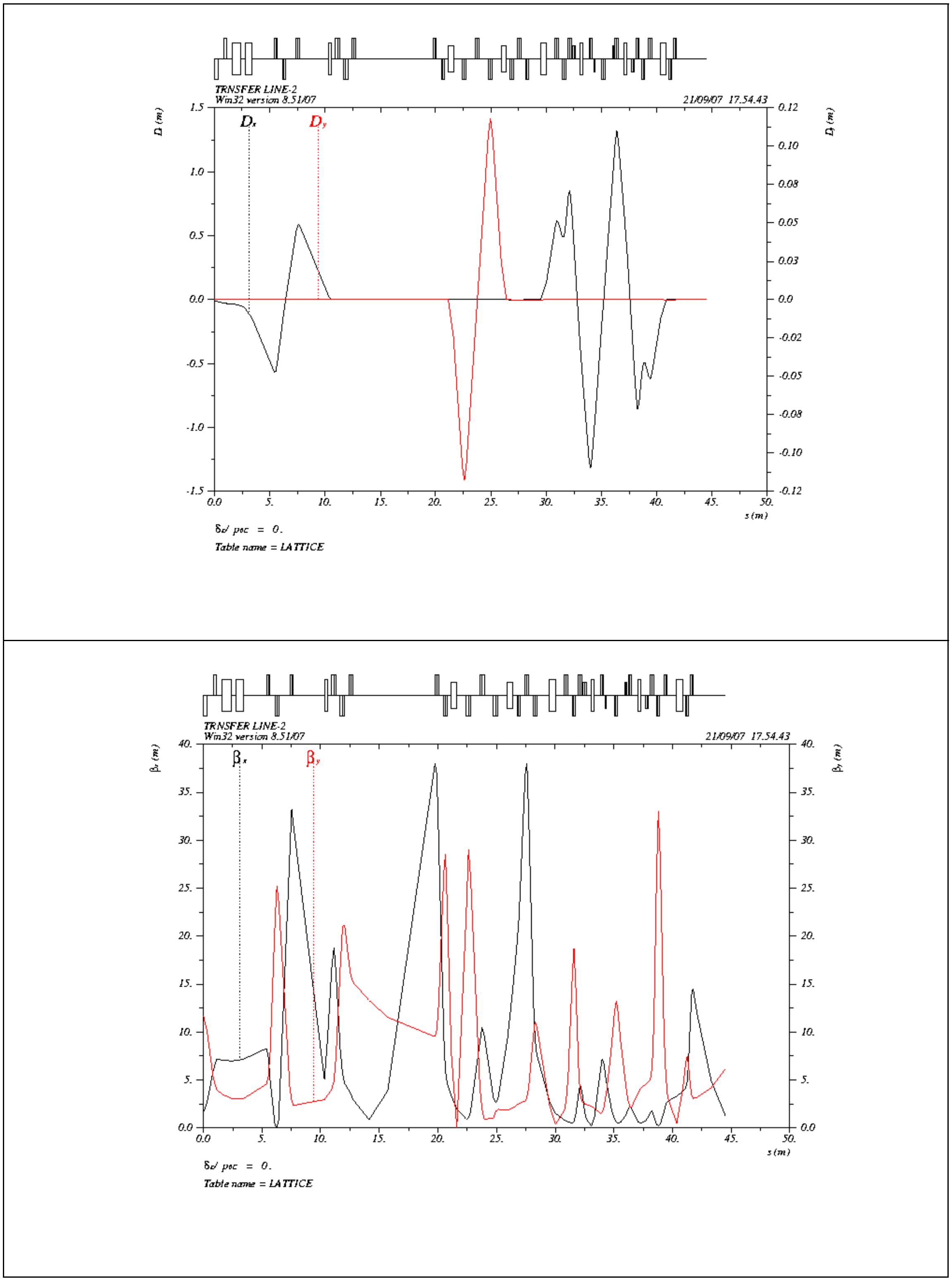


Figure-6L: Dispersion and beta functions @ R_{56} = +0.25m

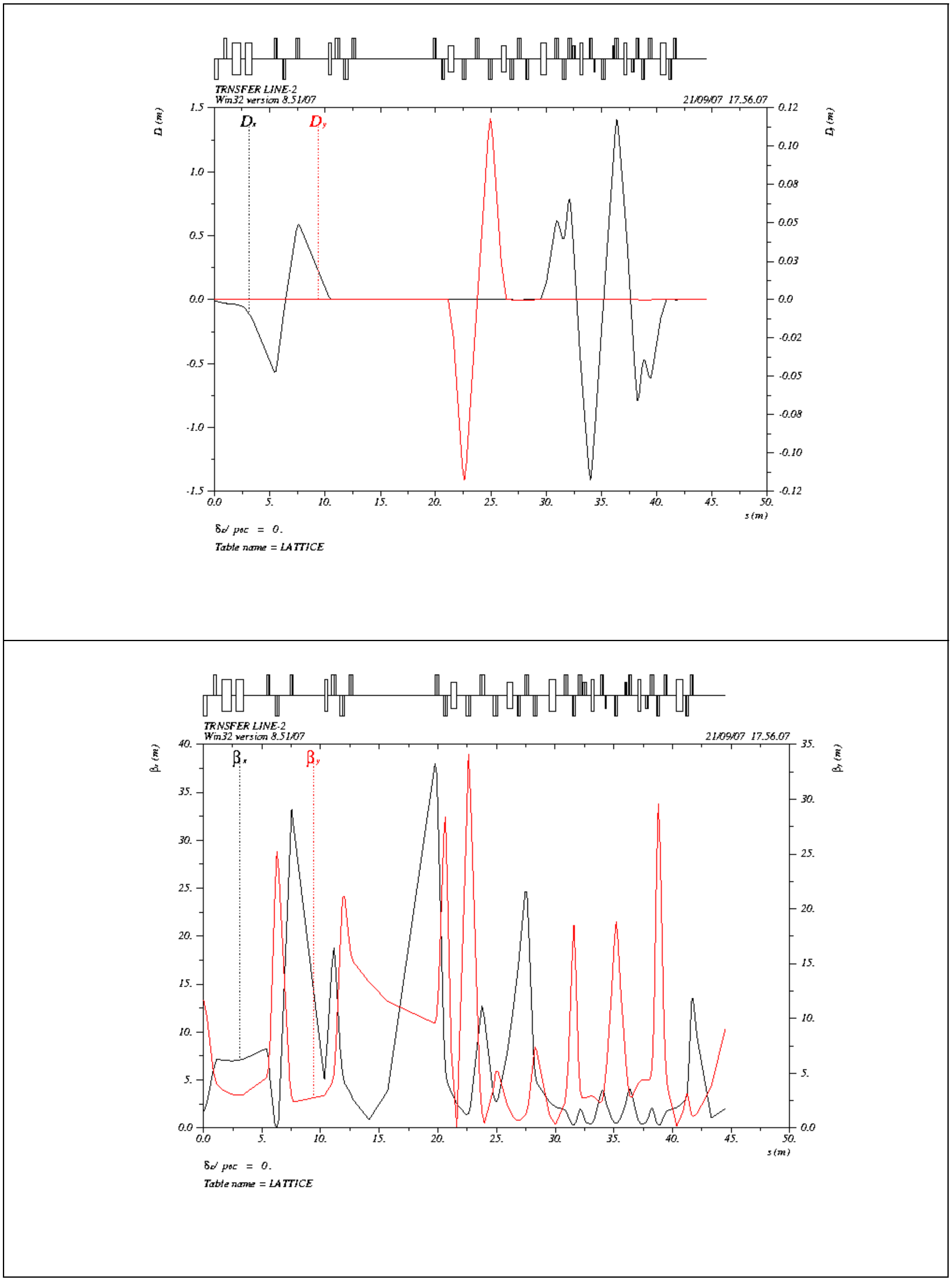


Figure-6M: Dispersion and beta functions @ R_{56} = +0.30m

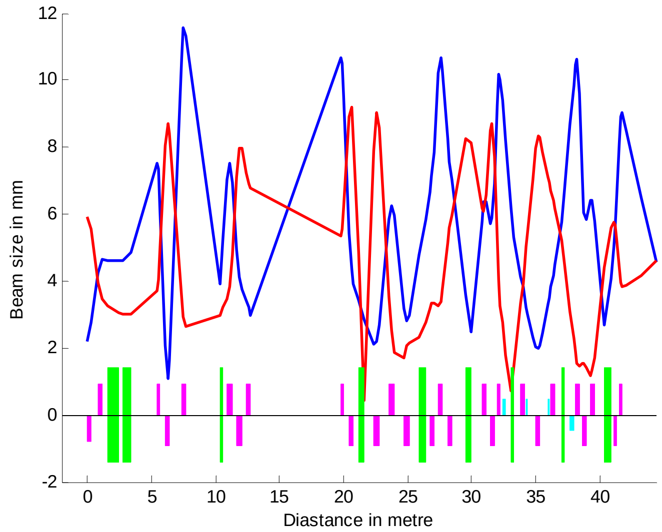


Figure-7A: Beam size in mm for the 1% momentum offset @ R_{56} = -0.30m (Blue: Horizontal and Red: Vertical plane)

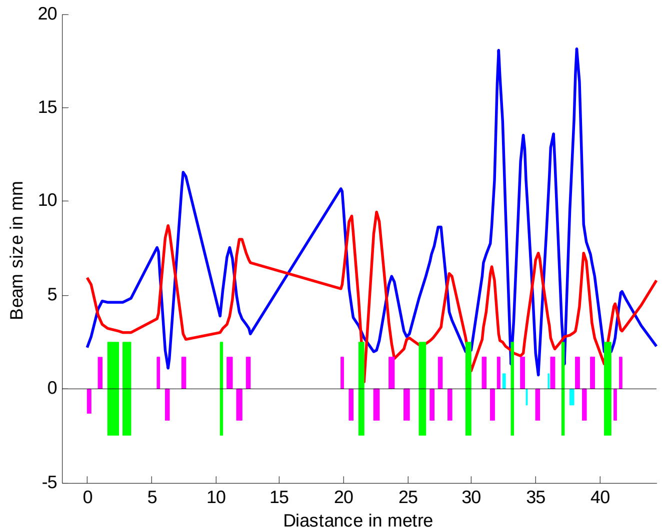


Figure-7B: Beam size in mm for the 1% momentum offset @ R_{56} = 0.00m (Blue: Horizontal and Red: Vertical plane)

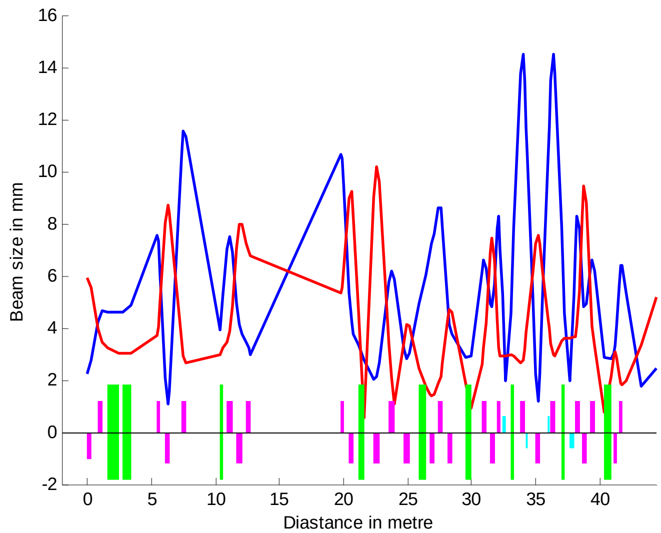


Figure-7C: Beam size in mm for the 1% momentum offset @ R_{56} = +0.30m (Blue: Horizontal and Red: Vertical plane)

5. T_{566} correction and Sextupole Optimization:

The path length dependence on momentum deviation has been studied taking into consideration first as well as second order effects. The parameter that connects the path length with square of the momentum deviation is the T_{566}, element of the second order transfer matrix, given by

$$\Delta l = -T_{566}\delta^2 \qquad [13]$$

Here we present the second order results in short. For detailed studies readers are referred to ***[3]***.

The momentum deviation of the particle, travelling through the cavity is modified in the presence of second order effect and is given by

$$\delta_1 = R_{65}z_0 + R_{66}\delta_0 + T_{655}z_0^2 + T_{666}\delta_0^2 + T_{656}z_0\delta_0$$

If we consider only energy-time correlation terms, this can be written down as

$$\delta_1 = R_{65}z_0 + T_{655}z_0^2 \qquad [14]$$

Cavity does not have any effect on z i.e.

$$z_1 = z_0 \quad [15]$$

Similarly for a magnetic channel (transfer line), the length-energy correlation can be written down as

$$z_2 = z_1 + R_{56}\delta_1 + T_{566}\delta_1^2 \quad [16]$$

Now combining these three equations (14, 15 and 16) yields the final z_2 in terms of initial z_0

$$z_2 = (1 + R_{56}R_{65})z_0 + \left(R_{56}T_{655} + R_{65}^2 T_{566}\right)z_0^2 \quad [17]$$

In the whole tuning range, we have made T_{566} zero. So in this line, the second order dependence comes through R_{56} and RF cavity parameters. Thus for a given cavity parameters, there will be a particular choice of R_{56}, which will give the maximum bunch compression. The wide tuning range of R_{56} in the line will provide a large set of RF parameters for which the minimum bunch length can be achieved. We do not include here the dependence on δ_0, which will restrict the possible range of the RF parameters, obtained barely from the above equation as a very large momentum deviation can not be transmitted through the transfer line.

Now we go through the sextupole scheme employed for T_{566} correction. Our design of the transfer line is constrained by the geometry, so there is not much flexibility in the adjustment of distances within the Module as well as in the location of the sextupoles, to obtain the desired betatron phase advances between them. Here we employ four sextupoles, driven by two power supplies to correct the second order longitudinal chromatic aberration T_{566}. We place these sextupoles close to quadrupoles to take advantage of higher dispersion function at these locations. The optimization of the line is done in such a way, that the phase space distortion due to these sextupoles up to 1σ is within the 10% in both the planes.

It is very difficult to get the *–I* transformer between the sextupoles in the entire range of tuning to suppress the phase space distortion. The sextupolar kick imparted by a sextupole depends not only its strength but also on the beta function and betatron phase, given by

$$\theta_x = \frac{1}{2}ml\left(x^2 - y^2\right) = \frac{1}{2}ml\left(\varepsilon_x\beta_x e^{i2\phi_x} - \varepsilon_y\beta_y e^{i2\phi_y}\right) \quad [14]$$

$$\theta_y = mlxy = ml\sqrt{\varepsilon_x\varepsilon_y\beta_x\beta_y}\,e^{i\phi_x}e^{i\phi_y} \quad [15]$$

Here symbols carry their usual meanings. We are looking for the phase space distortion, so here expressions are given for the on-momentum particle and dispersion dependent term is not included. It is clear that to suppress the sextupolar kicks; betatron function should be very small at the sextupoles. The correcting strength of the sextupoles for T_{566} is not affected much due to this as the strength is mainly governed by the dispersion function at the sextupoles. So for optimizing the phase space distortion, we have optimized the betatron functions at the sextupole location (for the given betatron phases), so that overall vector summation of sextupolar kicks, given by the equation 14 and 15 becomes very small. Without disturbing the dispersion distribution in Module-3, the optimization is possible by varying the initial conditions of Twiss parameters for Module-3. Thus we looked for the proper initial conditions of Twiss parameters, which generate the distribution of beta functions to minimize the sextupolar kicks, keeping constraint on maximum beta function. We also kept the sextupolar strengths symmetric to facilitate the use only two power supplies for driving the four magnets. In this way we have been able to suppress the phase space distortion using Q4, Q5, Q6, Q7 and Q8 quadrupoles (doublet and triplet in module-2). For optimizing this, a subroutine in the MATLAB was written. Figures show the phase space distortion for on and off momentum particles up to 2σ in normalized co-ordinates. These tracking results are obtained by the standard MATLAB routine LINEPASS of the Accelerator Tool Box. These phase space distortion studies do not include the effects of coherent synchrotron radiations (CSR). Table-6 shows the sextupole strength at different settings of R_{56} to compensate the effect of T_{566}. Figure-8 shows the phase space distortion in normalized co-ordinates, due to T_{566} correction in whole tuning range.

Table 6 (A) Sextupole Strengths (m^{-3}) for T_{566} Correction

Sextupole	R_{56} settings (m)						
	-0.30	**-0.25**	**-0.20**	**-0.15**	**-0.10**	**-0.05**	**0.00**
SX1	41.368925	26.797500	32.094230	42.307200	39.357680	42.531715	41.779525
SX2	OFF	OFF	OFF	OFF	-88.703140	-94.505860	-119.552150
SX3	OFF	OFF	OFF	OFF	88.703140	94.505860	119.552150
SX4	-41.368925	-26.797500	-32.094230	-42.307200	-39.357680	-42.531715	-41.779525
T_{566} without sextupoles (m)	-3.871	-41.910	-37.205	-22.733	-25.272	-26.783	-27.650
T_{566} after correction (m) $\times 10^{-4}$	-7.443	3.358	-0.73	3.547	2.847	-9.118	-7.575

Table 6 (B) Sextupole Strengths (m^{-3}) for T_{566} Correction

Sextupole	R_{56} settings (m)					
	0.05	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**
SX1	42.006775	41.902875	43.538175	43.616720	43.700000	43.703990
SX2	-112.543600	-115.361700	-127.993550	-126.457750	-154.538700	-135.895150
SX3	112.543600	115.361700	127.993550	126.457750	154.538700	135.895150
SX4	-42.006775	-41.902875	-43.538175	-43.616720	-43.700000	-43.703990
T_{566} without sextupoles (m)	-31.541	-32.462	-28.467	-27.724	-16.761	-17.661

T_{566} after correction (m) $\times 10^{-4}$	7.005	-4.847	3.552	-3.760	-4.252	-3.200

R_{56}=-0.30

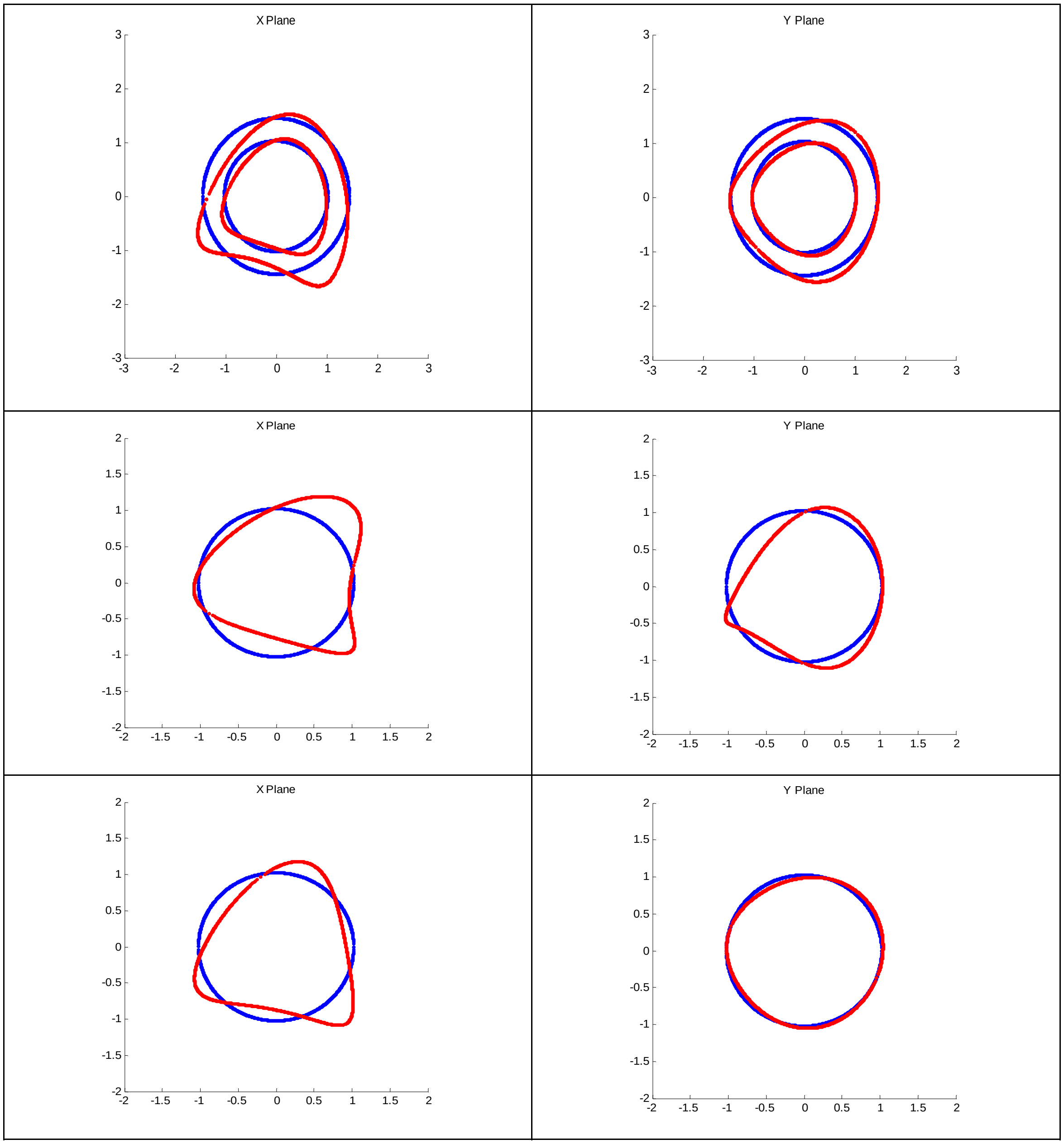


Figure-8A: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=-0.25

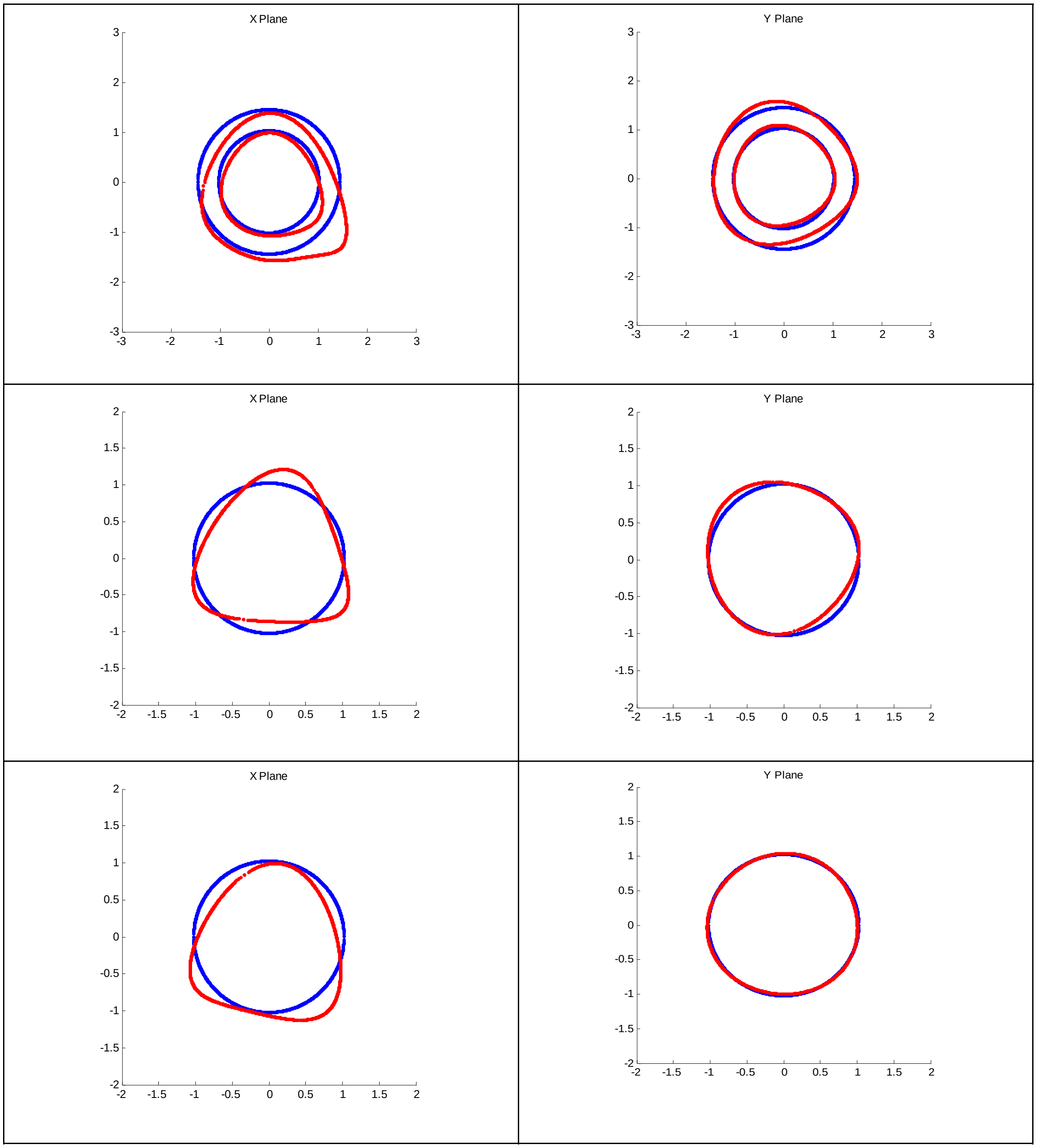


Figure-8B: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum

deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles

R_{56}=-0.20

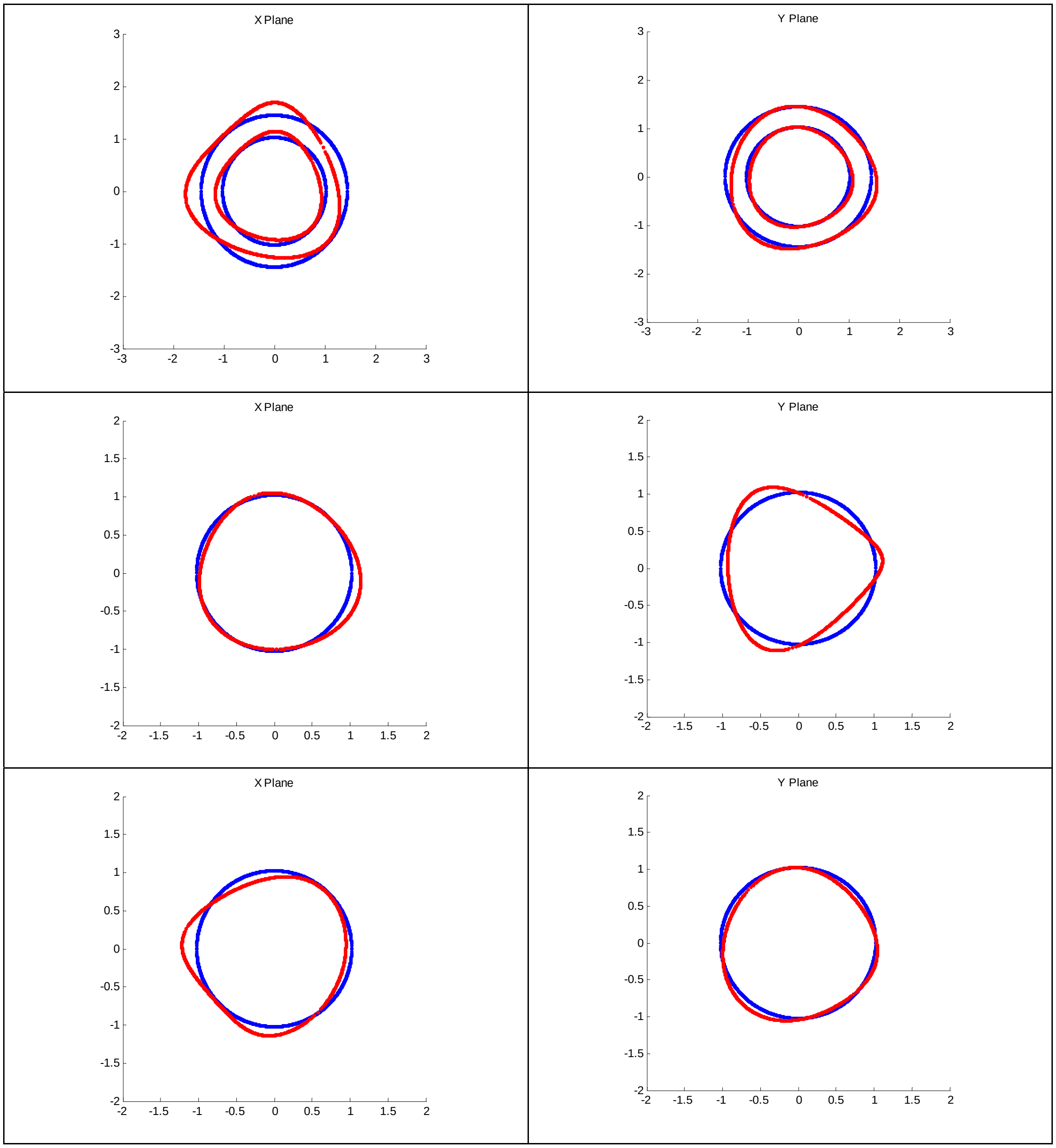


Figure-8C: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=-0.15

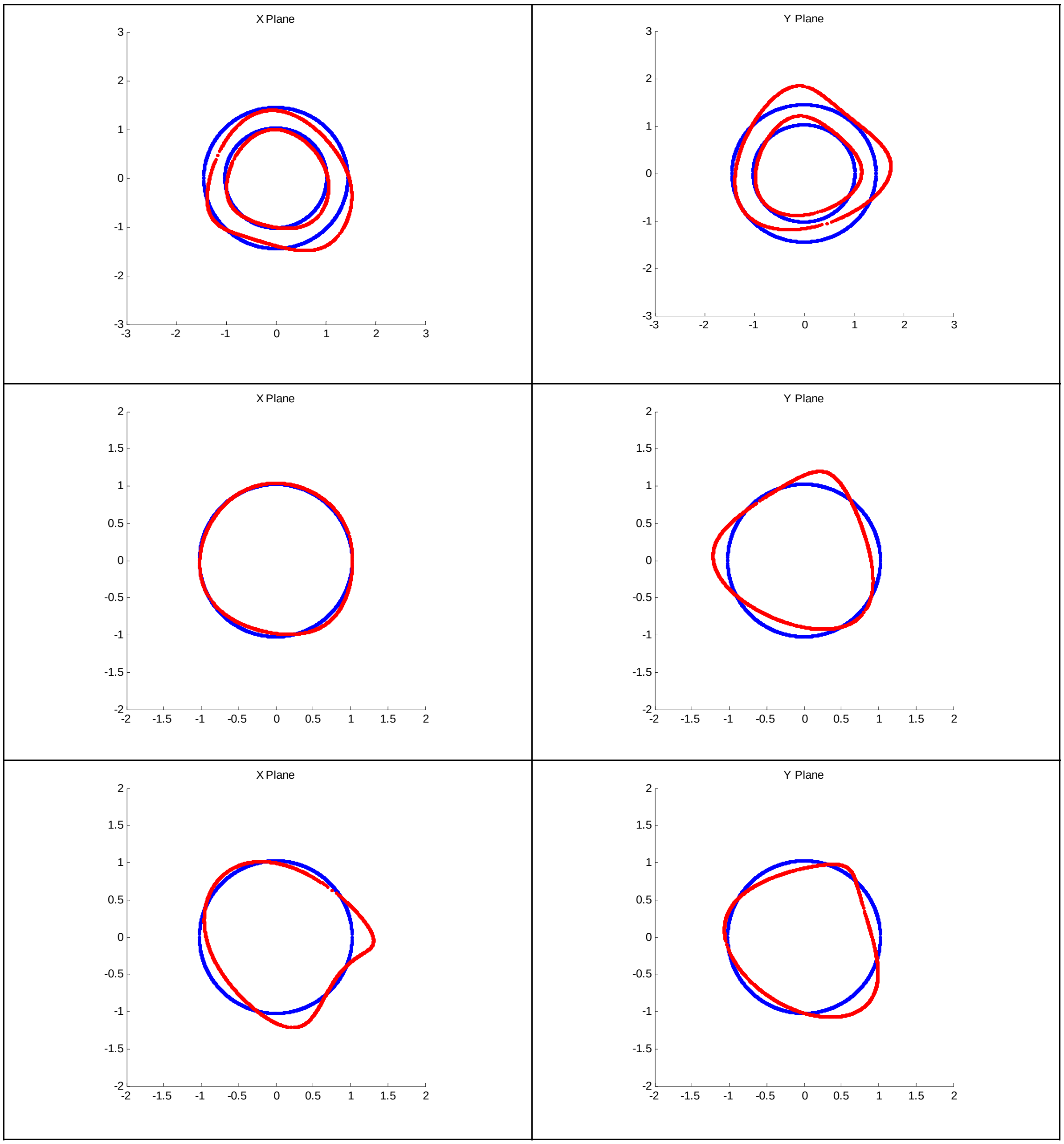


Figure-8D: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum

deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=-0.10

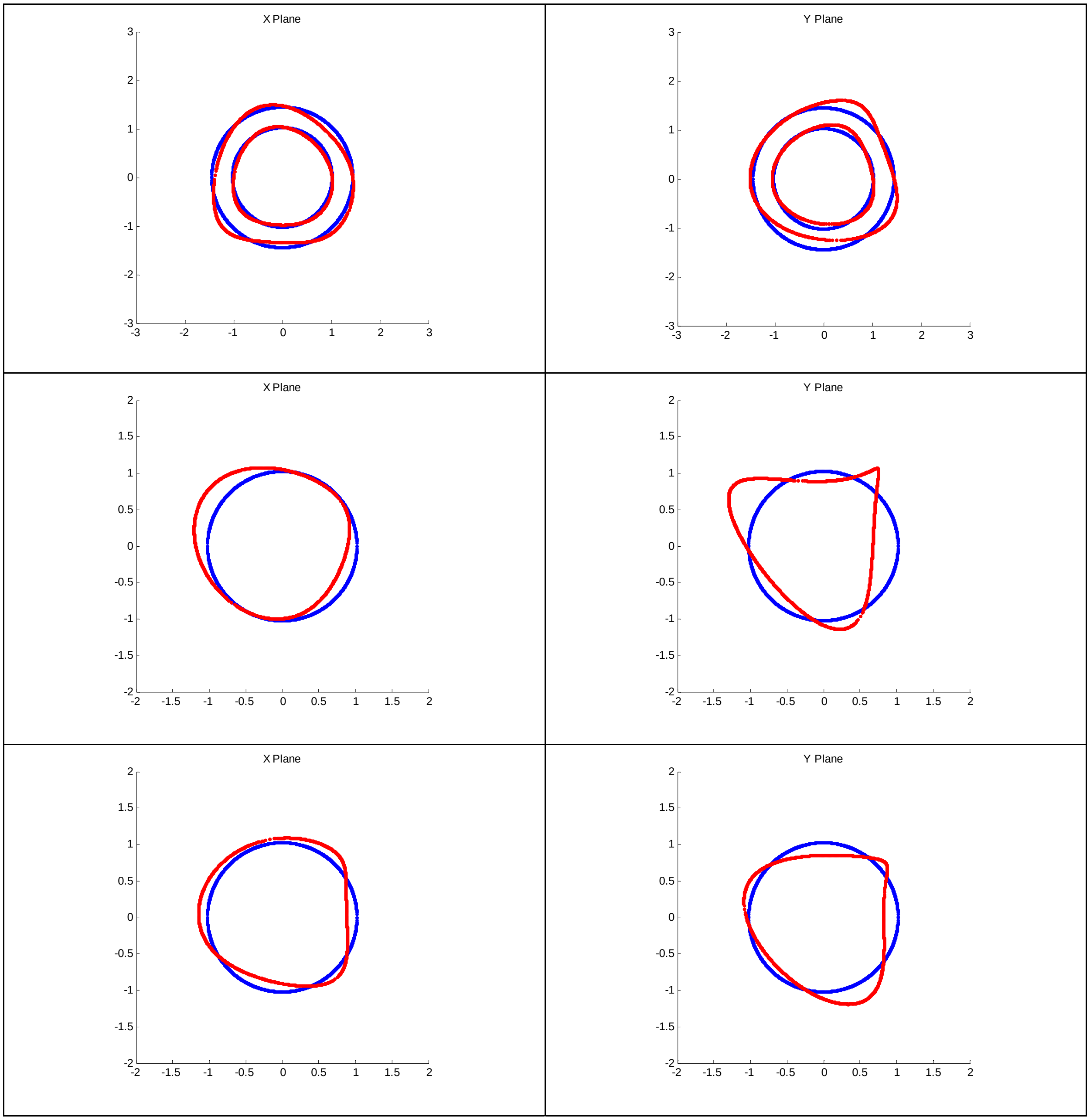


Figure-8E: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=-0.05

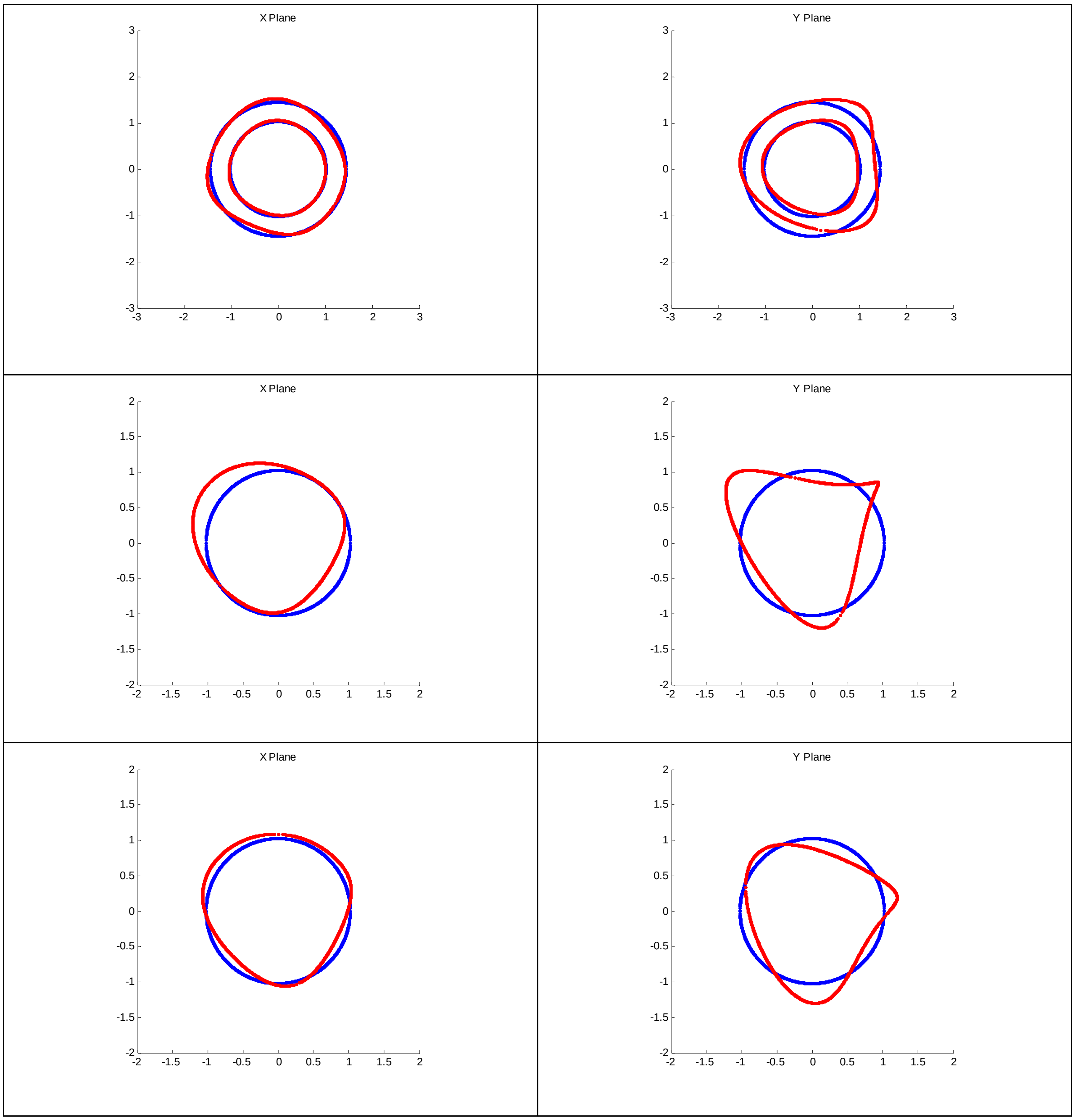

X Plane
Y Plane
X Plane
Y Plane
X Plane
Y Plane
3
2
1
0
-1
-2
-3
1.5
0.5
-0.5
-1.5

Figure-8F: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.00

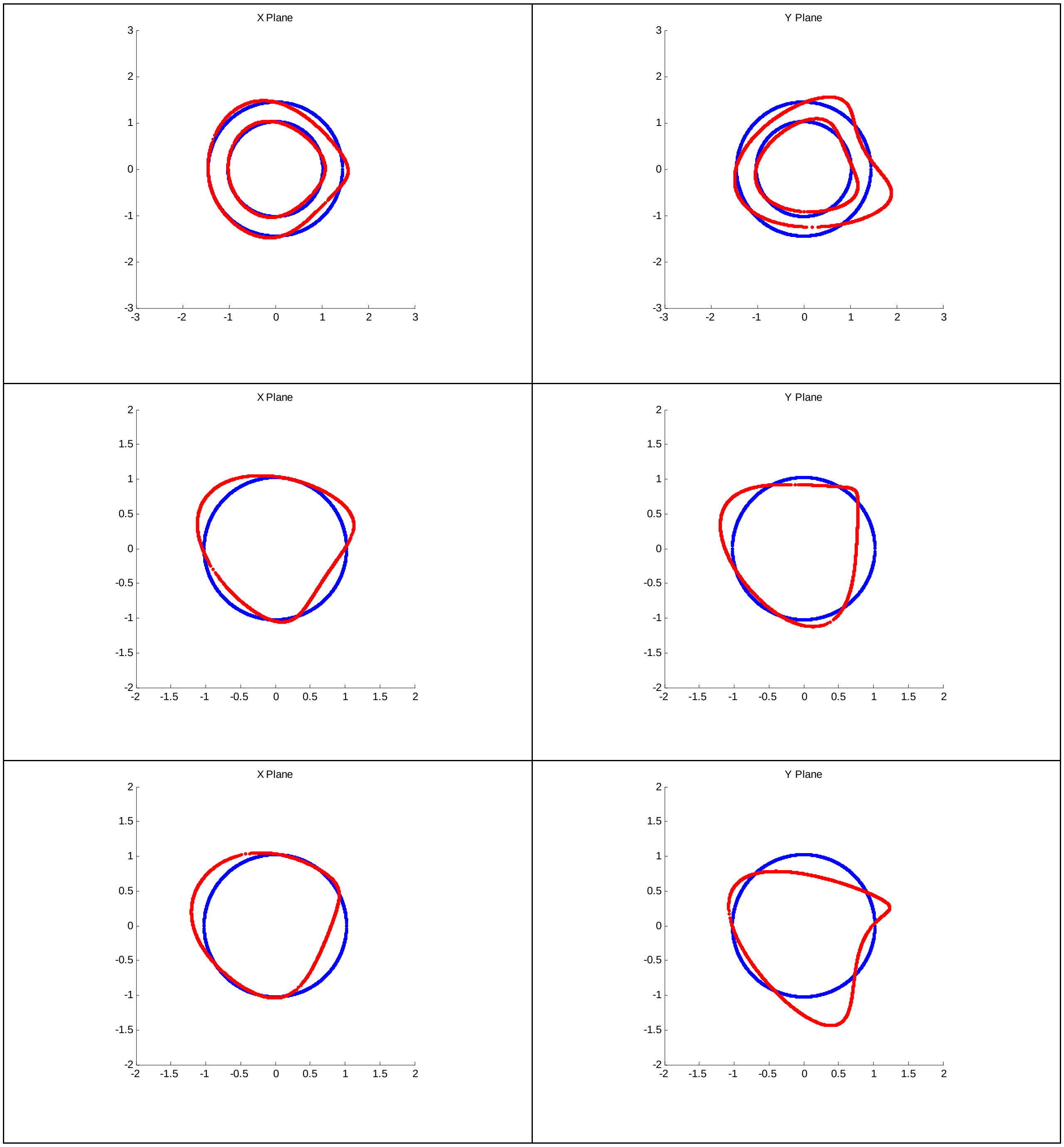


Figure-8G: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.05

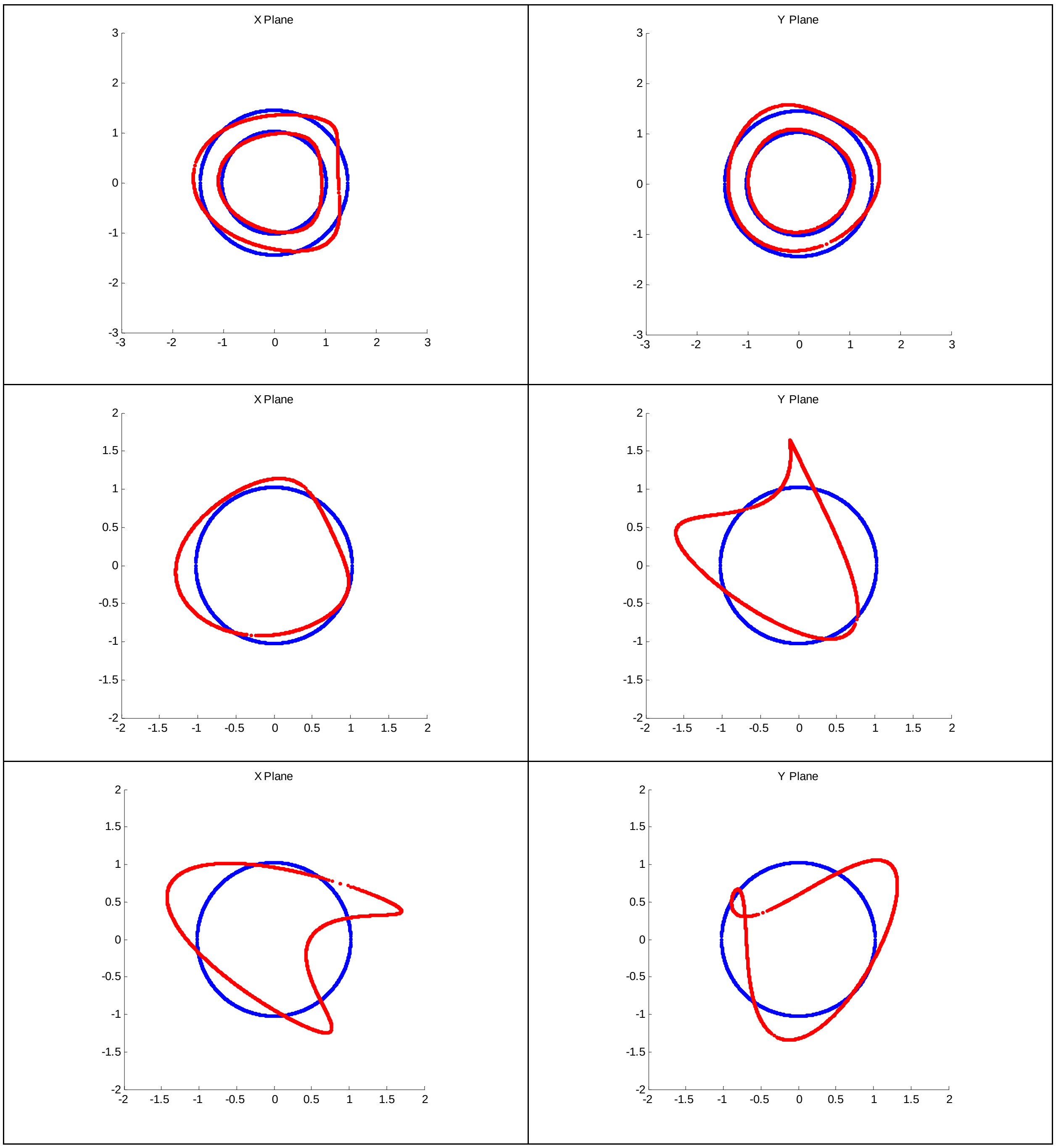


Figure-8H: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.10

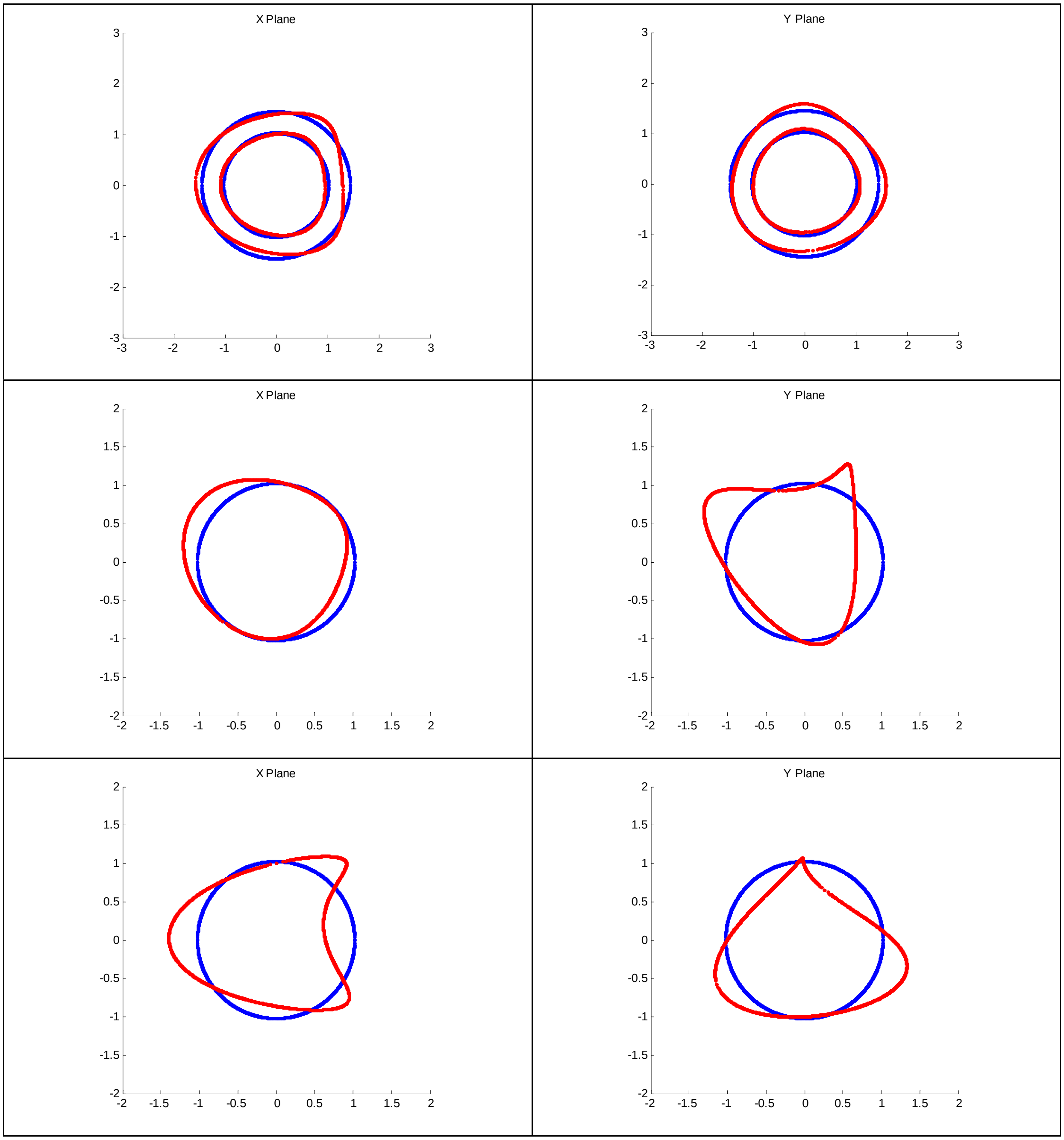


Figure-8I: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.15

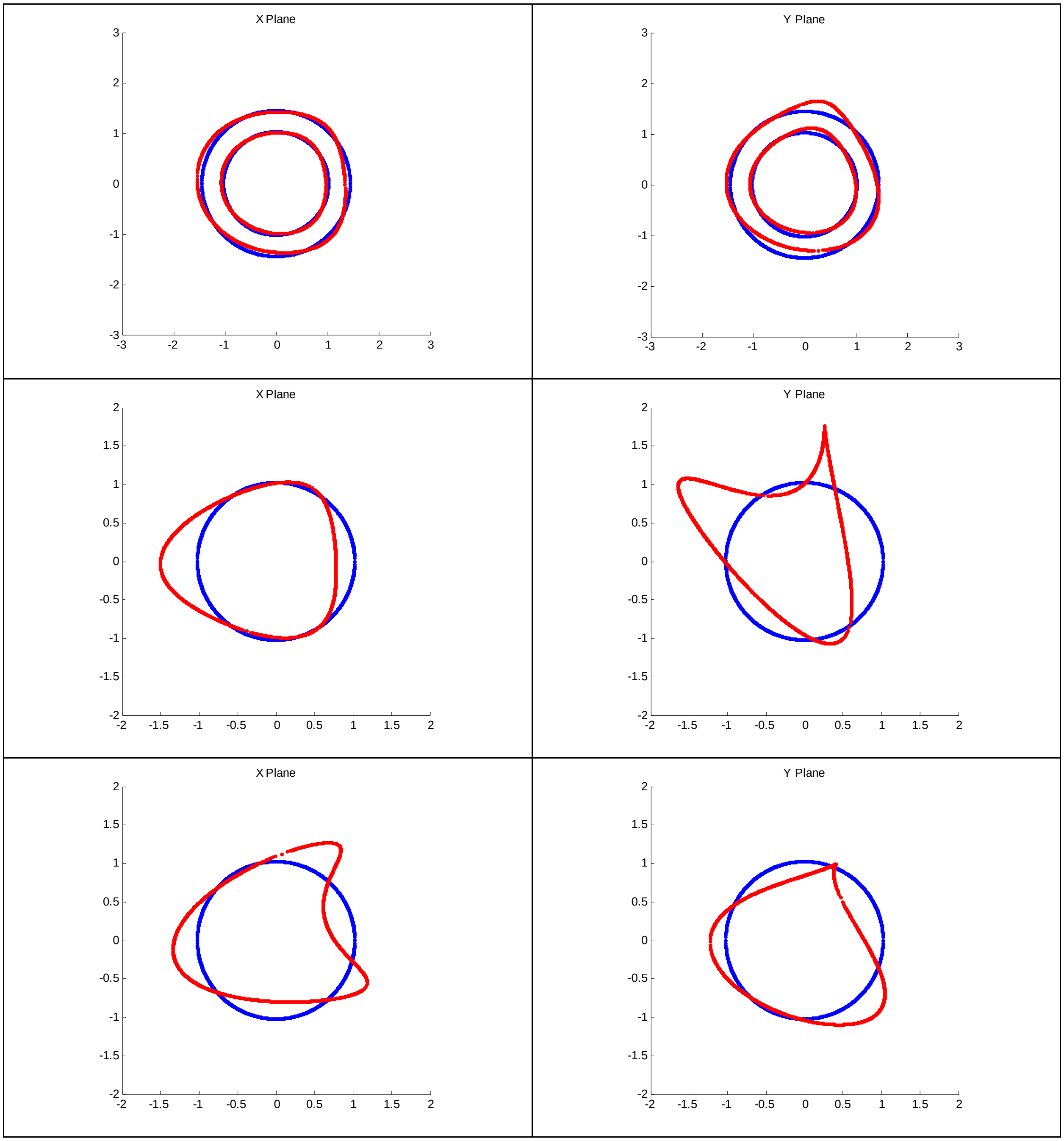


Figure-8J: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.20

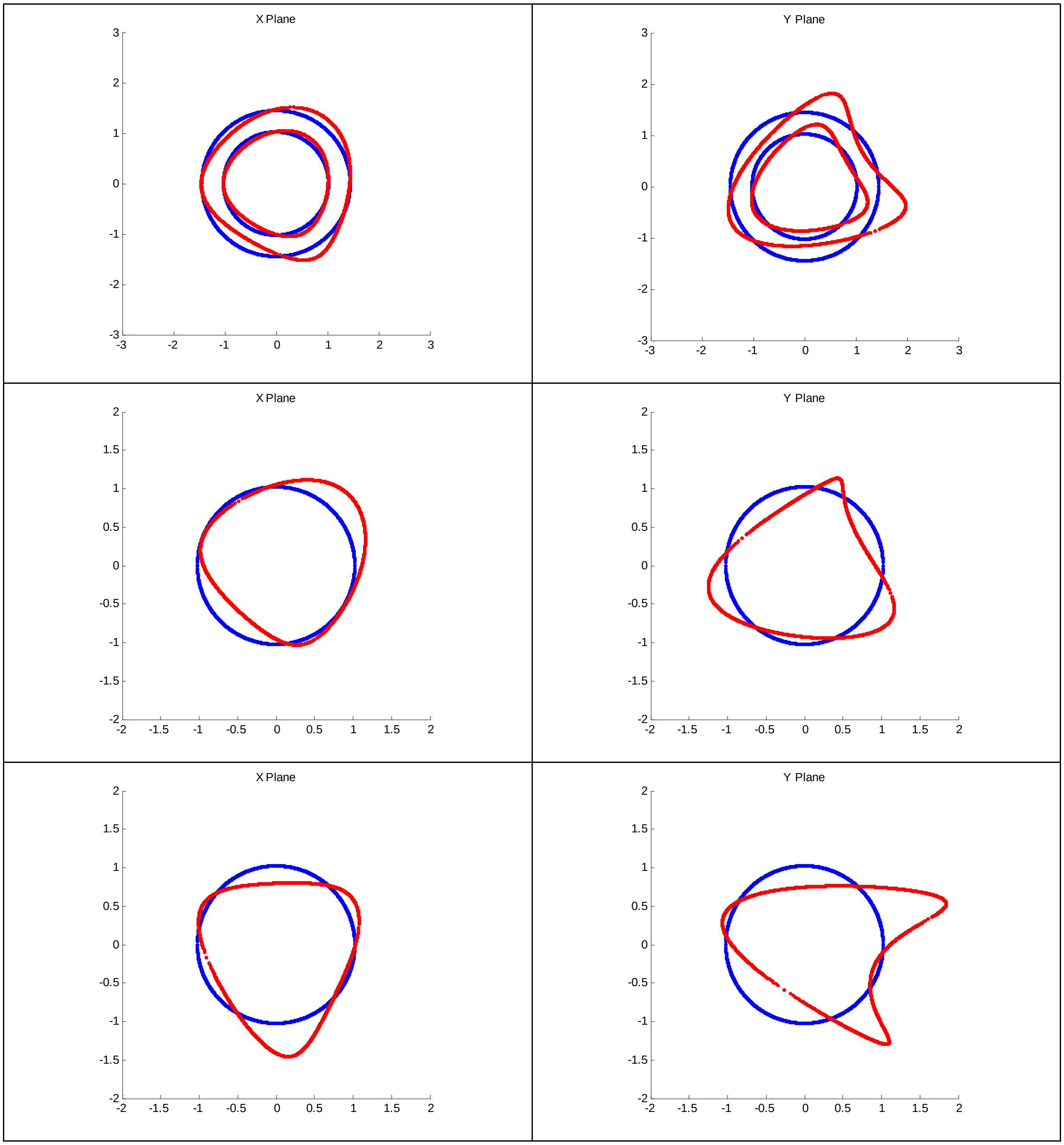


Figure-8K: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupolesσ.

R_{56}=0.25

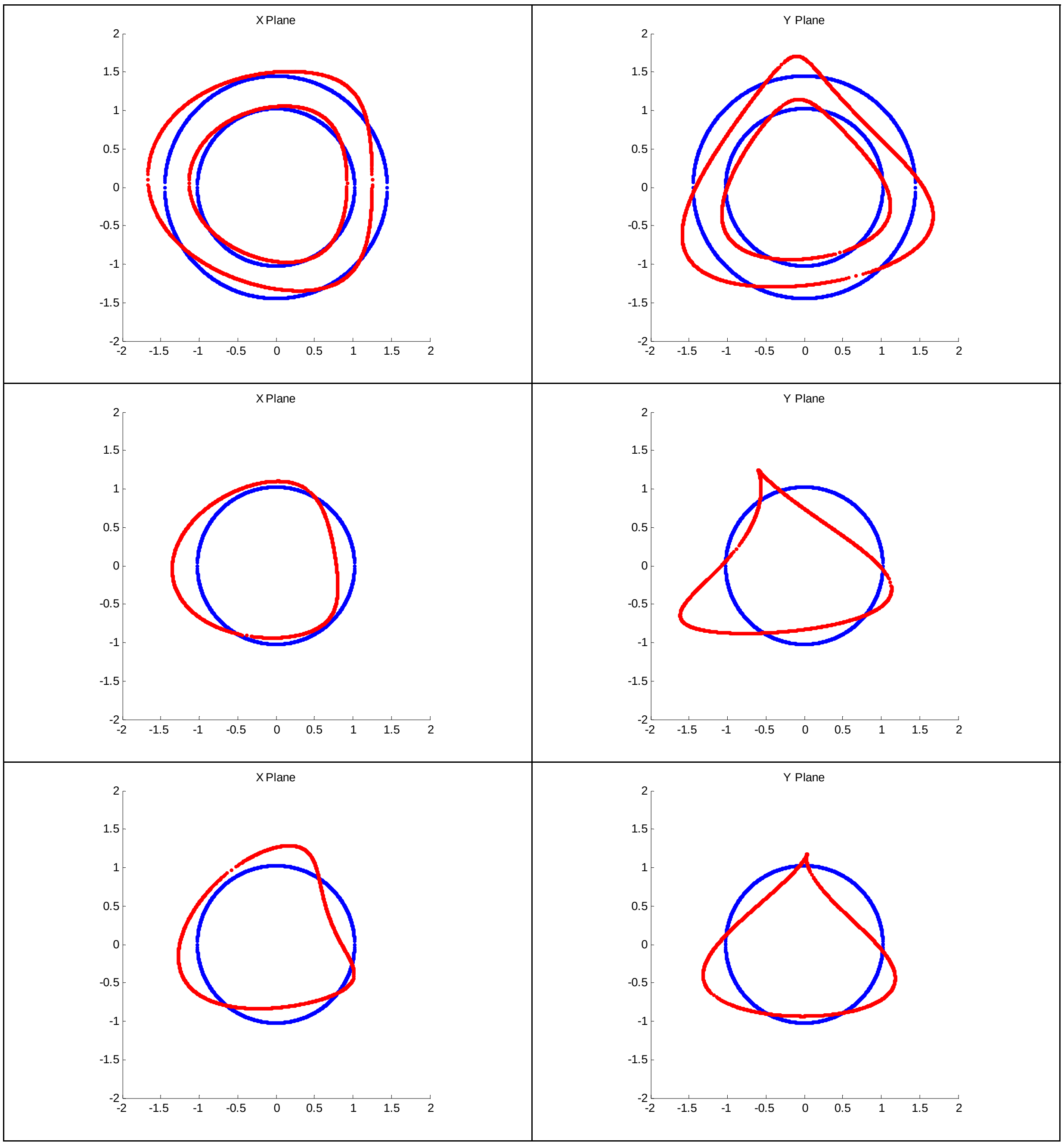


Figure-8L: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

R_{56}=0.30

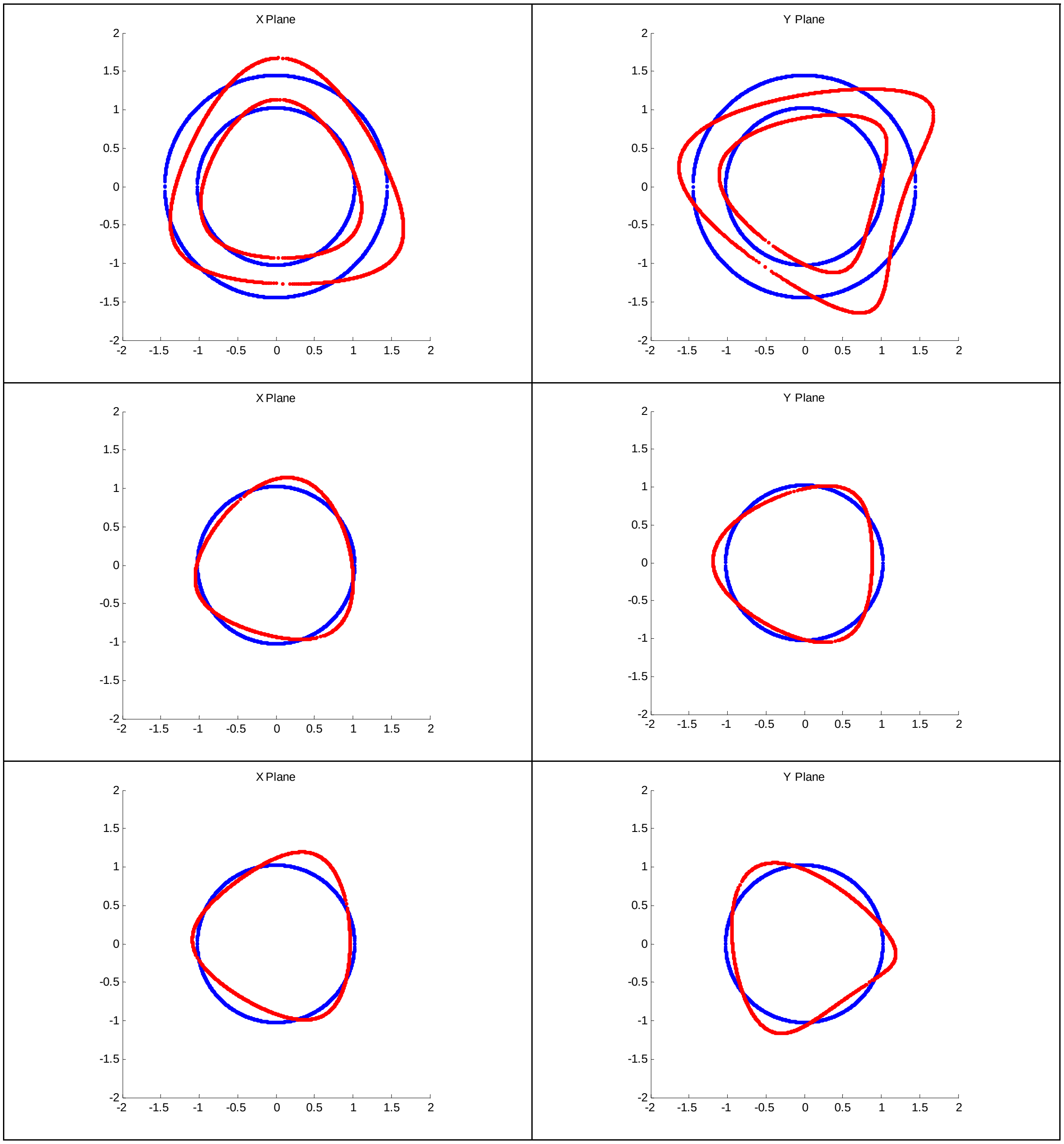


Figure-8M: Phase space (Normalized) distortion due to T_{566} correction. Here the first row shows the on-momentum particle for 1σ and 2σ and second and third row shows the particle with momentum deviation of +1% and -1% respectively, up to 1σ. Figure in red colour shows the distorted phase space in the presence of sextupoles and figure in blue shows the phase space without sextupoles.

6. Low Dispersion mode of TL-2:

In the design discussed earlier, we increased the dispersion to suppress T_{566} with the sextupoles within the specified strengths. In the initial run of the transfer line, when sextupoles are not operated, we can obtain the desired R_{56} with lower values of dispersion function, which also decreases the quadrupole strengths. Due to lower quadrupole strengths, the line will be more rigid from misalignment error point of view and also natural T_{566} will be lower. The lower dispersion will keep the overall beam size smaller and therefore there will be more room in the vacuum chamber for the beam transmission. This will ease the operation during initial stages of commissioning. In these initial runs, by running the line in this relaxed mode, it can be characterized more accurately as the linear model will be very similar to the real one. Keeping these points in view, we have carried out the optical design of the TL-2 with low dispersion mode for R_{56} = -0.30m, -0.25m, 0.00 and +0.30m. Specifically, R_{56} = -0.25m is included as it is the required nominal operating point. Table-7 shows the required quadrupole strengths for this mode. Figures-9 shows the betatron and dispersion function for this low dispersion mode.

Table 7 Quadrupole strengths for low dispersion mode optics

Quadrupole & Type	**R_{56} settings (m)**			
	-0.30	**-0.25**	**0.00**	**+0.30**
Q0A [Slim]	5.499300			
Q0B [Slim]	-4.889800			
Q0C [TSL]	4.528500			
Q1 [Standard]	3.668100	3.874428	3.668100	3.843000
Q2 [Standard]	-3.876300	-2.947592	-3.876300	-3.801100
Q3 [Standard]	1.950700	0.6759084	1.950700	1.637200
Q4 [TSL]	3.836500	3.612900	3.836500	3.810100
Q5 [TSL]	-6.240200	-5.839600	-6.240200	-6.323200
Q1V [Standard]	-4.939900			
Q2V [Standard]	3.247453			
Q6 [TSL]	-0.9445672	-1.899700	-0.734800	-0.671300
Q7 [TSL]	4.320893	4.980700	4.085400	3.885500
Q8 [TSL]	-2.760655	-2.694100	-2.855600	-2.699187
QC1 [TSL]	3.840300	5.085700	5.121500	6.421631
QC2 [TSL]	-0.460300	-2.117900	-0.411500	-0.1912914
QC3 [TSL]	0.452900	OFF	0.437400	0.181764
QC4 [TSL]	4.226300	4.806300	4.025500	4.162491
QC5 [TSL]	-3.877169	-4.725600	-3.761000	-3.729488
QD1 [Q3L]	-1.846345	-5.756300	-4.360100	-4.426516
QD2 [Q3L]	1.489854	9.791100	5.957600	5.440047

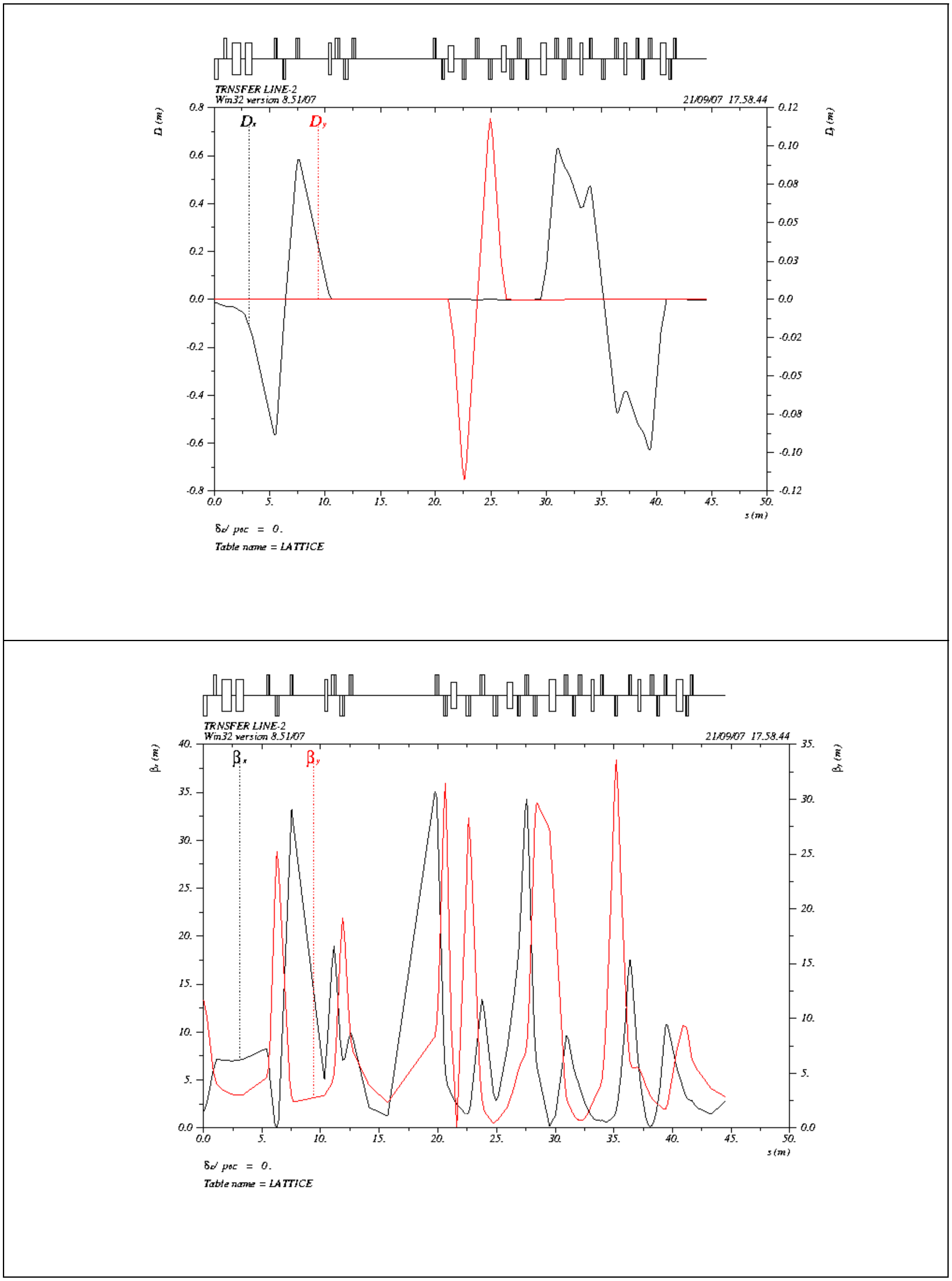


Figure-9A: Dispersion and beta functions @ R_{56} = -0.30m

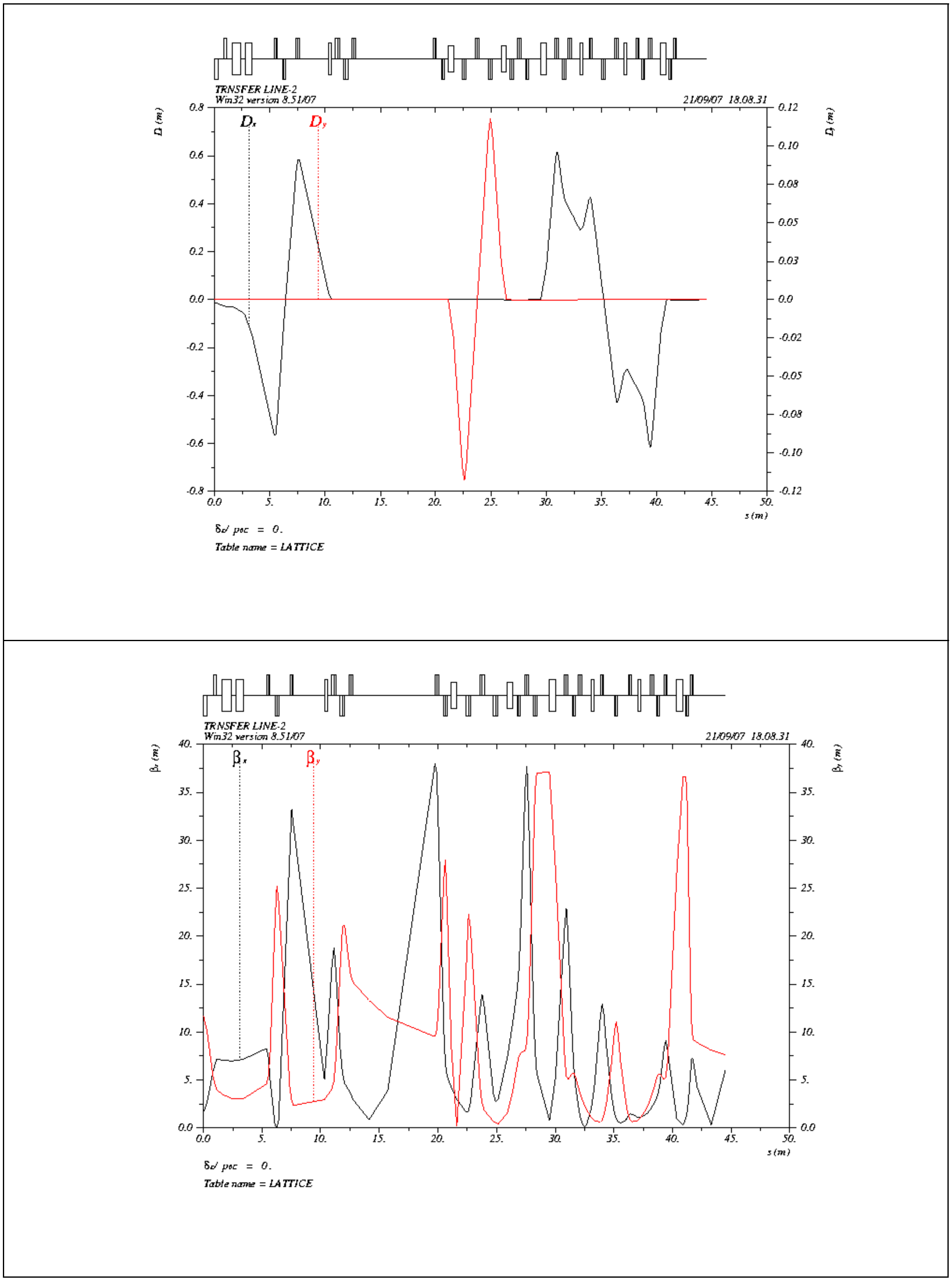


Figure-9B: Dispersion and beta functions @ R_{56} = -0.25m (Proposed nominal operating point)

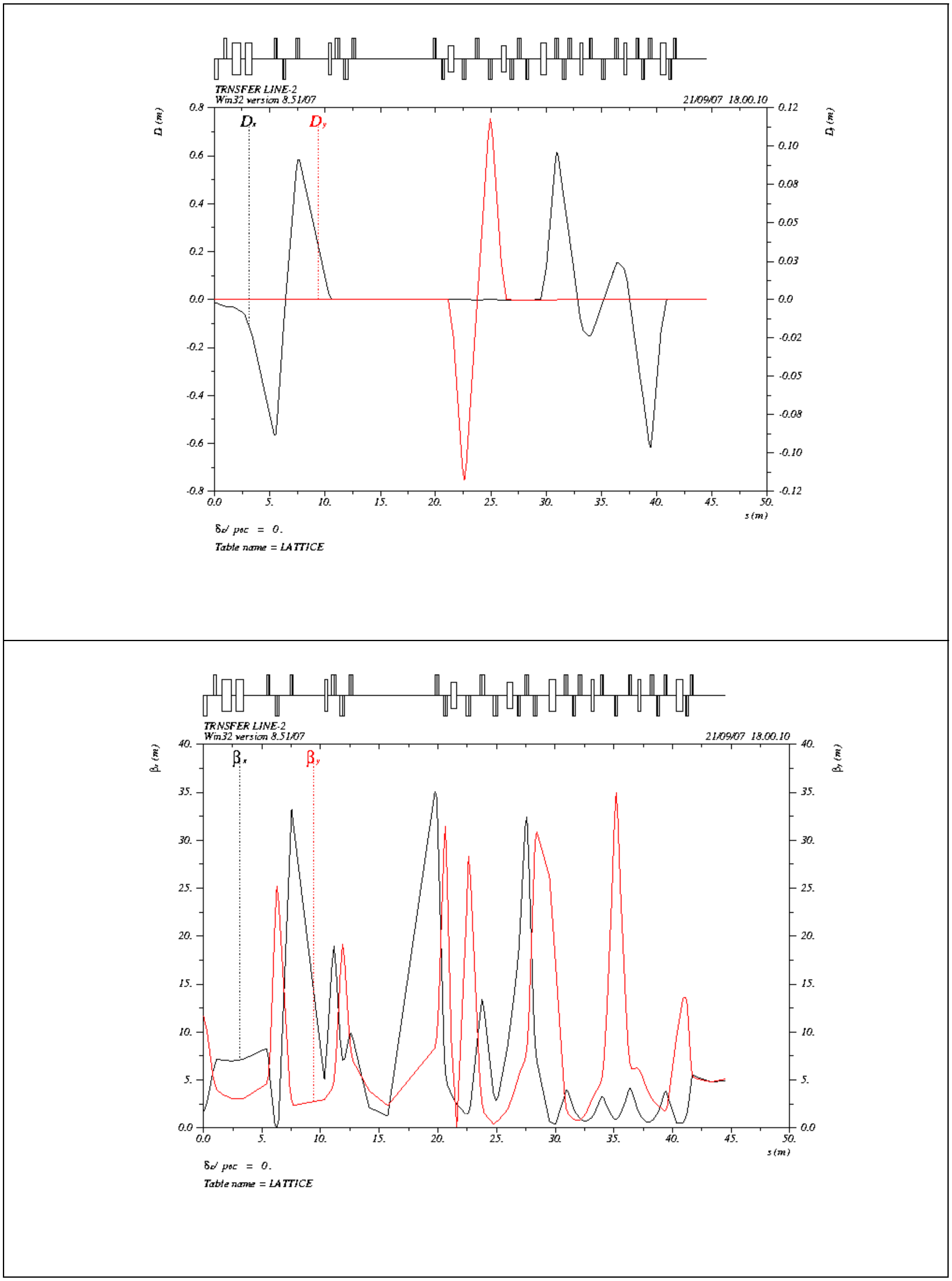
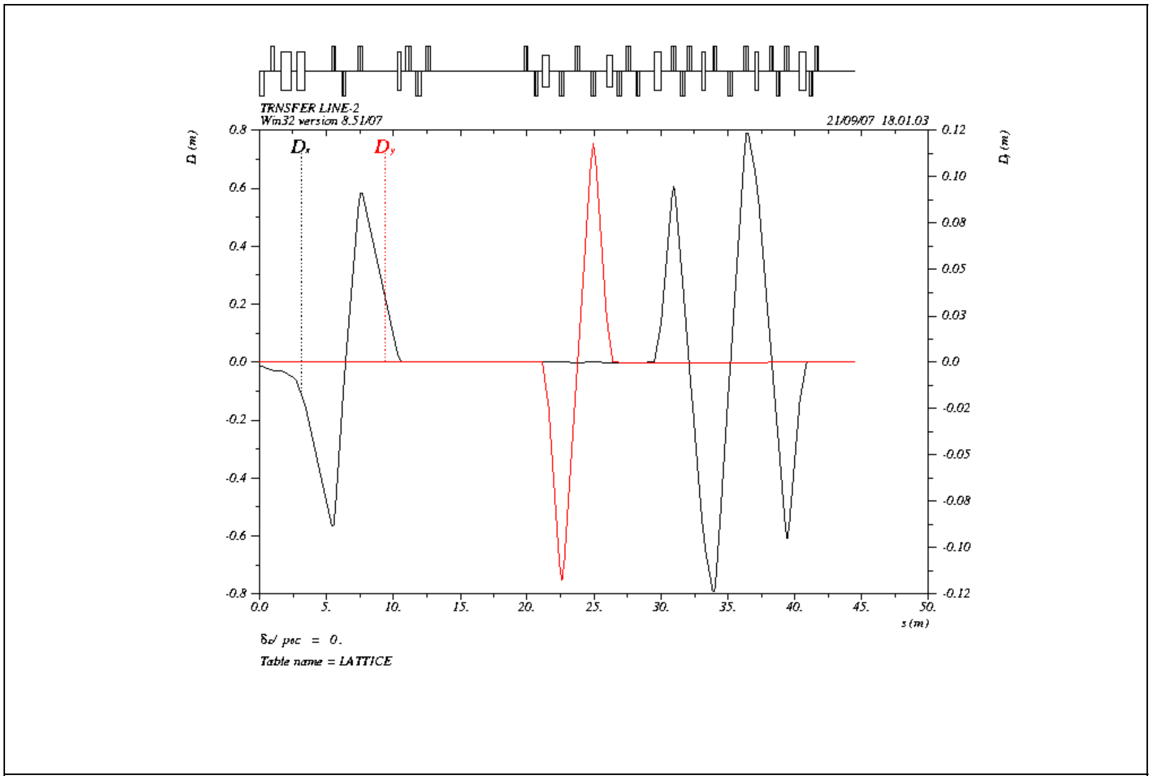


Figure-9C: Dispersion and beta functions @ R_{56} = 0.00m



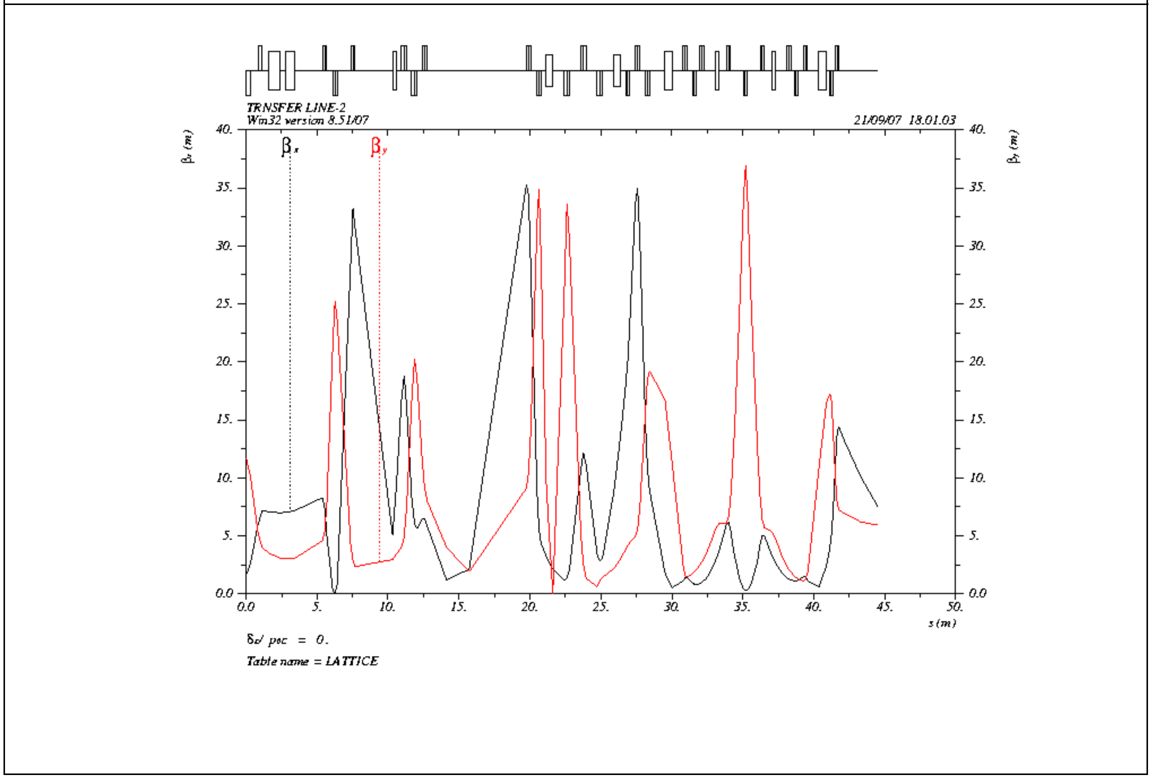


Figure-9D: Dispersion and beta functions @ R_{56} = +0.30m

7. Conclusion:

The optical design of the Transfer Line (TL-2) from the Combiner Ring to the CLEX area has been completed. The line meets all the geometrical and magnetic constraints. This line is capable of tuning the R_{56} parameter from -0.30m to +0.30m. The line is also corrected up to second order longitudinal chromatic aberration i.e. T_{566}, in entire range of tuning and the phase space distortion due to this second order correction is kept within 10% in both the planes. The studies do not include effects of the CSR.

8. Acknowledgement:

We acknowledge the valuable guidance, suggestions, feedback and encouragement received from Dr. H. Braun, Dr. G. Geschonke and Dr. F. Tecker of CERN from time to time, which have helped us immensely in carrying out this work. We also thank Dr V C Sahni and Mr S Kotaiah for their constant encouragement and support during the course of these studies.

9. References:

1. Ed. G.Gaschone and A.Ghigo, “CTF3 Design Report”, CERN/PS/2002-008 (RF).
2. R. Corsini etal, “Overview of CLIC and CTF-3”, CERN/PS/2002-073, CLIC Note 540.
3. Andy Wolski, “A short introduction to bunch compressors for linear colliders”, Note for USPAS course on linear colliders, June 2003.
4. E.T.d’Amico and G.Guignard, “Special Lattice Computation for the CERN Compact Linear Collider”, Physical Review Special Topics-Accelerators and Beams, Volume-4, 021002 (2001).

10. Appendix:

In this appendix, the input file of MAD 8 is provided for the TL-2 of CTF3. The file provided is for R_{56} = +0.30m i.e. of extreme positive R_{56} optics. The files for other R_{56} can be obtained just by changing the quadrupole and sextupole strengths.

<u>Input file for MAD 8</u>

```
TITLE,"TRNSFER LINE-2"
ASSIGN,PRINT="TL2OUT_2007"

!ENERGY - 300 MeV
!Length - ~44.5m
!THIS FILE IS FOR THE TL-2CTF3

!FILE FOR R56 = +0.30m

!   COMPLETE SPECIFICATIONS OF THE CR-QUAD-CENTRE TO SEPTUM (from MAD-X file of
CERN)

!     Drifts for the longex2x-------

LL2I:DRIFT, L=0.52200000
LL3A:DRIFT, L=1.14600000
LL3B:DRIFT, L=1.24000000
LL4I:DRIFT, L=0.54000000
LL1I:DRIFT, L=0.83636117
LL5I:DRIFT, L=0.48373883

!     Quads for the longex2x--------

Q510:QUADRUPOLE, L=0.32800,   K1=3.286251212195
Q540:QUADRUPOLE, L=0.16400,   K1=-1.51209300000
Q560:QUADRUPOLE, L=0.30000,   K1=-1.966076623307
Q580:QUADRUPOLE, L=0.30000,   K1=2.168966412347

!     Septums & Kickers for ext -----

SEP1:SBEND, L=0.782258104274,   ANGLE=-0.048332194571, &
            E1=-0.044495868125, E2=-0.38363265e-2

!   Septum definition if -1*EXA in EXTA is not to be done-----
!SEP1:SBEND, L=0.782258104274,   ANGLE=-0.048332194571, &
!            E1=-0.38363265e-2, E2=-0.044495868125

SEP2:RBEND, L=0.650000000000,   ANGLE=-0.161107315569, &
            E1=0.000,    E2=0.000
KKEX:KICKER, L=0.00, HKICK=0.01000, VKICK=0.0000000

!     Drifts for ext ----------------
DOUT:DRIFT, L=0.2500000000
DSEP:DRIFT, L=0.3494677098

!   COMPLETE ELEMENT-SPECIFICATION OF MODULE-1

!     Bend magnets and septa--------
BM0 :RBEND, L=0.2669594, ANGLE=0.209439510239, E1=0.0, E2=0.0

!     Drift spaces--------
```

```
!------ Lengths are changed as the distance of module-2 from parallel wall is
decreased.

DA1 :DRIFT, L=1.988600
DA2 :DRIFT, L=0.429500
DA3 :DRIFT, L=0.961700
!DA4 :DRIFT, L=2.858200
DA4 :DRIFT, L=2.858200-0.21589269

!     Quadrupoles--------
Q0A :QUADRUPOLE, L=0.150000, K1=5.499300
Q0B :QUADRUPOLE, L=0.150000, K1=-4.889800
Q0C :QUADRUPOLE, L=0.147500, K1=4.528500

!   COMPLETE ELEMENT-SPECIFICATION OF MODULE-2

!     Drift spaces--------
DB1 :DRIFT, L=0.3518448   !0.351848m => ~12cm mech. gap in BM and stnd. qdpr.
DB2 :DRIFT, L=0.3500000   !0.35m => 13.8cm gap between mech. edge to edge for
stnd qdpr.
DB3 :DRIFT, L=0.3500000
DB4A:DRIFT, L=1.3452080   !Space before the emergency exit.
DB4B:DRIFT, L=1.6000000   !Space in front of emergency exit.
DB4C:DRIFT, L=4.0342135   !Space after emergency exit for the tail clippers.
DB5 :DRIFT, L=0.4400000   !0.44m => ~30.5cm gap between mech. edge to edge for
TSL qdpr.
DB6 :DRIFT, L=0.3500000
DB7 :DRIFT, L=0.3500000
DB8 :DRIFT, L=0.4020000   !0.402m => ~26cm gap between mech .edge to edge for
TSL qdpr.
DB9 :DRIFT, L=0.4020000
DB10:DRIFT, L=1.072483409


!     Quadrupoles--------
QB1  :QUADRUPOLE, L=0.190000, K1=3.874428
QB2  :QUADRUPOLE, L=0.190000, K1=-2.947592
QB3  :QUADRUPOLE, L=0.190000, K1=0.6759084

QB4  :QUADRUPOLE, L=0.147500, K1=3.71460
QB5  :QUADRUPOLE, L=0.147500, K1=-6.29940

QB6  :QUADRUPOLE, L=0.147500, K1=-0.00040
QB7  :QUADRUPOLE, L=0.147500, K1=3.90490
QB8  :QUADRUPOLE, L=0.147500, K1=-5.06410

!     Vertical achromat elements--------
MAG1V:SBEND, L=0.47000, ANGLE=0.10472,  E1=0.0, E2=0.0, TILT
MAG2V:SBEND, L=0.47000, ANGLE=-0.10472, E1=0.0, E2=0.0, TILT
Q1V  :QUADRUPOLE, L=0.190000, K1=-4.9399
Q2V  :QUADRUPOLE, L=0.190000, K1=3.247453
D1V  :DRIFT,L=0.80000
D2V  :DRIFT,L=0.786478    !~57cm mech gap between two stnd qdpr.

!   COMPLETE ELEMENT-SPECIFICATION OF MODULE-3

!     Bend magnets--------
BM1 :RBEND, L=0.5099835, ANGLE=0.536688744988, E1=0.0, E2=0.0    !30.75 deg.
BM2 :RBEND, L=0.2669594, ANGLE=0.301069295969, E1=0.0, E2=0.0    !17.25 deg
bend, used in tuning of R56. (Edge of this magnet is nearest to wall)
BM3 :RBEND, L=0.2669594, ANGLE=-0.301069295969, E1=0.0, E2=0.0
BM4 :RBEND, L=0.5099835, ANGLE=-0.536688744988, E1=0.0, E2=0.0

!     Drift spaces--------
```

```
DQSX=0.184500       !Min possible distance bet SX-QD (6.5cm Mech)

DC1 :DRIFT, L=0.7893000     !~47cm mech gap between BM and qdpr.
DC2 :DRIFT, L=0.3484400     !~31cm mech gap between qdpr.

DC3 :DRIFT, L=0.2354        !Changed length of DC3 after the mail of H.Braun
DC4 :DRIFT, L=0.1245000
DC5 :DRIFT, L=0.4254675

!Changed lengths for getting the proper optimized solutions
DC6 :DRIFT, L=0.5200000
DC7 :DRIFT, L=0.1375000
DC8 :DRIFT, L=0.4099700
DC8A:DRIFT, L=0.092947
DC8B:DRIFT, L=DC8A[L]+0.1475

!----Lengths are changed to fit in the building------

DD1 :DRIFT, L=0.2531276     !~9cm mech gap between BM-qdpr.
DD2 :DRIFT, L=0.1760000
DD3 :DRIFT, L=0.3305000
DD4 :DRIFT, L=1.2000000

!     Quadrupoles--------
QC1 :QUADRUPOLE, L=0.147500, K1=5.009872
QC2 :QUADRUPOLE, L=0.147500, K1=-8.401705
QC3 :QUADRUPOLE, L=0.147500, K1=9.964513

QC4 :QUADRUPOLE, L=0.147500, K1=5.789055
QC5 :QUADRUPOLE, L=0.147500, K1=-4.053587
!-------Mirror

QD1 :QUADRUPOLE, L=0.113000, K1=-10.57458
QD2 :QUADRUPOLE, L=0.113000, K1=8.581195

!     Sextupoles--------
SX1 :SEXTUPOLE, L=0.246000/2.0, K2=43.703990
SX2 :SEXTUPOLE, L=0.100000/2.0, K2=-135.895150
SX3 :SEXTUPOLE, L=0.100000/2.0, K2=135.895150
SX4 :SEXTUPOLE, L=0.246000/2.0, K2=-43.703990

!      Markers----------
MCR4:MARKER
MCR5:MARKER
MCR6:MARKER
MCR7:MARKER

MCR1:MARKER
MCR2:MARKER

MD11:MARKER
MD12:MARKER

M001:MARKER
M002:MARKER

MSX1:MARKER
MSX2:MARKER
MSX3:MARKER
MSX4:MARKER

M3A:MARKER
M3B:MARKER
```

```
ME  :MARKER


!   LINE DEFINITION (DIFFERENT MODULES & COMPLETE LINE)
!============================================================

!         Below is the part from centre of Q540 and without DOUT----

EXA1: LINE=(MCR4, SEP2, MCR5, DSEP, MCR6, SEP1, MCR7)
EXTA: LINE=(-1*(EXA1))


!   Line definition after the kicker (extraction) of CR -----------
LX2X: LINE=(MCR1, Q560, LL4I, Q580, LL5I, MCR2)
TLEX: LINE=(LX2X, EXTA)

!--------CR and EXT part completed----------

!     Line specifications and definition of module-1 ------
MOD1:LINE=(MD11,DA1,Q0A,Q0A,DA2,Q0B,Q0B,DA3,Q0C,Q0C,DA4, &
     BM0,MD12)

!     Line specifications and definition of module-2 ------

ARC1:LINE=(DB1,Q1,Q1,DB2,Q2,Q2,DB3,Q3,Q3,DB4A,DB4B,DB4C)
ARC2:LINE=(Q4,Q4,DB5,Q5,Q5,DB6)
ARC3:LINE=(DB7,Q6,Q6,DB8,Q7,Q7,DB9,Q8,Q8,DB10)
ARCH:LINE=(MAG1V,D1V,Q1V,Q1V,D2V,Q2V,Q2V,D2V,Q1V,Q1V,D1V,MAG2V)
MOD2:LINE=(M001,ARC1,ARC2,ARCH,M002,ARC3)

!     Line specifications and definition of module-3 ------

ARC4:LINE=(BM1,DC1,QC1,QC1,DC2,QC2,QC2,DC3,QC3,QC3,DC4,   &
           SX1,MSX1,SX1,DC5)

!   Definition using symmetric power supplies with four quads------
ARC5:LINE=(BM2,DC6,QC4,QC4,DC7,SX2,MSX2,SX2,DC8,DC8B,QC5,QC5, &
          DC8B,DC8,SX3,MSX3,SX3,DC7,QC4,QC4,DC6)

!   Definition using symmetric power supplies ------

ARC6:LINE=(BM3,DC5,SX4,MSX4,SX4,DC4,QC3,QC3,DC3,QC2,QC2,DC2, &
          QC1,QC1,DC1,BM4)

ARC7:LINE=(DD1,QD1,QD1,DD2,QD2,QD2,DD3,DD4,ME,DD4)
MOD3:LINE=(M3A,ARC4,ARC5,ARC6,M3B,ARC7)

! ===========  Complete line definition =================
TL2C:LINE=(TLEX,MOD1,MOD2,MOD3)

USE,TL2C,RANGE=#S/#E

BEAM, Particle=electron,&
EX=100.0e-06,EY=100.0e-06,&
ENERGY=0.300
PRINT,#S/E

!--- Twiss parameters at the centre of Q540 ----


TWISS,COUPLE,DELTAP=0.0000,LINE=TL2C,BETX=1.625100,BETY=11.72000, &
ALFX=-0.766300,ALFY=-0.903800,DX=-0.01240,DPX=-0.01000, &
DY=0.00000,DPY=0.00000,SAVE=LATTICE
```

```
PLOT,COLOUR=100,HAXIS=S,VAXIS1=BETX,VAXIS2=BETY, &
FILENAME="OPTICS_TL2_revised_2007"
PLOT, COLOUR=100, HAXIS=S, VAXIS1=DX, VAXIS2=DY, &
FILENAME="OPTICSDP_TL2_revised_2007"
PLOT, COLOUR=100, HAXIS=S, VAXIS1=MUX, VAXIS2=MUY, &
FILENAME="OPTICSph_TL2_revised_2007"

STOP
```