Study of a Proposed Injection and new extraction Systems for the Fermilab Booster

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1 Conclusions

New injection scheme reduces vertical β-function by 23% from 27.3 m to 22.1 m.

There is a horizontal closed orbit deviation of ~ 2.5 *mm* at injection because of gradient term in the bump magnets. It can be corrected by two fast (20-turn ramp) correctors of BL=0.005 kG-m.

Nonlinear field in the orbit bump magnets do not give a visible effect to the beam parameters during injection.

Table 1: The expansion coefficients ($d^n BL/dx^n$), with respect to magnet center in the injection system bump magnets. $B \cdot L = B_o \cdot L + \Sigma(1/n! \cdot d^n BL/dx^n \cdot x^n)$

magnet	b0	b1	b2	b3	b4	b5	b6
	$T-m$	$T-m/inch$	$T-m/inch^2$	$T-m/inch^3$	$T-m/inch^4$	$T-m/inch^5$	$T-m/inch^6$
1	1.557373-01	2.76408e-04	2.0488e-05	1.50762e-04	2.94144e-04	-2.8224e-04	-3.08952e-03
2	-1.557373-01	2.76408e-04	-2.0488e-05	1.50762e-04	-2.94144e-04	-2.8224e-04	3.08952e-03
3	-1.557373-01	-2.76408e-04	-2.0488e-05	-1.50762e-04	-2.94144e-04	2.8224e-04	3.08952e-03
4	1.557373-01	-2.76408e-04	2.0488e-05	-1.50762e-04	2.94144e-04	2.8224e-04	-3.08952e-03

Table 2: The field harmonics ($b_n = [1.e+04/(B_o \cdot L \cdot (n-1)!)] * d^{n-1}BL/dx^{n-1}$) in the injection system bump magnets.

magnet	b0	b2	b3	b4	b5	b6	b7
	$T-m$						
1	7.5431E-02	-0.76	6.2	0.230	-0.06	-0.056	-0.067
2	-7.5431E-02	0.84	-6.4	-0.157	0.22	-0.047	-0.203
3	-7.5431E-02	-0.62	-6.6	-0.060	-0.06	0.080	0.106
4	7.5431E-02	-0.01	5.8	-0.062	0.03	0.550	-0.060

Table 3: The MAD program multipole coefficients of the order n with respect to the magnet center $K_n \cdot L = 1/(B \cdot \rho) d^n BL/dx^n = 1/(3.3356405 \cdot 0.954263) d^n BL/dx^n [m^{-n}]$ for 0.4 GeV protons at new injection and extraction bump magnets. Input data to STRUCT code. Harmonics in a bump(max) are shown for maximum field in the magnet. Harmonics in a bump2a are shown for a case of bump2 rotated in the horizontal plane by 180°. Bump(max) and bump2 are not used in the system.

element	BL	$K_1 \cdot L$	$K_2 \cdot L$	$K_3 \cdot L$	$K_4 \cdot L$	$K_5 \cdot L$	$K_6 \cdot L$
	T-m	$1/m$	$1/m^2$	$1/m^3$	$1/m^4$	$1/m^5$	$1/m^6$
New injection bump magnets							
bump(max)	+1.5574E-01	+3.4188E-03	+9.9767E-03	+2.8903E+00	+2.2201E+02	-8.3869E+03	-3.6144E+06
bump1	-7.0028E-02	-1.5373E-03	-4.4860E-03	-1.2996E+00	-9.9829E+01	+3.7712E+03	+1.6252E+06
bump2	+1.4006E-01	+3.0745E-03	+8.9721E-03	+2.5993E+00	+1.9966E+02	-7.5424E+03	-3.2505E+06
bump2a	+1.4006E-01	-3.0745E-03	+8.9721E-03	-2.5993E+00	+1.9966E+02	7.5424E+03	-3.2505E+06
bump3	-7.0028E-02	-1.5373E-03	-4.4860E-03	-1.2996E+00	-9.9829E+01	+3.7712E+03	+1.6252E+06
New extraction bump magnets							
bump1	+7.5431E-02	-7.0906E-05	+4.5547E-02	+1.9956E-01	-8.1984E+00	-1.5063E+03	-3.5475E+05
bump2	-7.5431E-02	-7.8369E-05	+4.7016E-02	+1.3622E-01	-3.0061E+01	+1.2642E+03	+1.0748E+06
bump3	-7.5431E-02	+5.7844E-05	+4.8485E-02	+5.2060E-02	+8.1984E+00	-2.1518E+03	-5.6125E+05
bump4	+7.5431E-02	-9.3297E-07	+4.2608E-02	-5.3795E-02	+4.0992E+00	+1.4794E+04	-3.1769E+05

Table 4: The MAD program multipole coefficients of the order n with respect to the beam position in the magnet aperture $K_n \cdot L = 1/(B \cdot \rho) d^n BL/dx^n = 1/(3.3356405 \cdot 0.954263) d^n BL/dx^n [m^{-n}]$ for 0.4 GeV protons at new injection and extraction bump magnets. Injection system: circulating beam is located at X=-40.0 mm from magnet center at bump1 and bump3, and at X=+4.4 mm from magnet center at bump2. Extraction system: circulating beam is located at Y=0 from magnet center at all bump magnets. Input data to MAD code.

element	BL	$K_1 \cdot L$	$K_2 \cdot L$	$K_3 \cdot L$	$K_4 \cdot L$	$K_5 \cdot L$	$K_6 \cdot L$
	T-m	$1/m$	$1/m^2$	$1/m^3$	$1/m^4$	$1/m^5$	$1/m^6$
New injection bump magnets							
bump(max)	+1.5526E-01	+5.1535E-03	-2.2411E-01	+2.5854E+01	-2.3341E+03	+1.0409E+08	-3.6144E+06
bump1	-6.9814E-02	-2.3173E-03	+1.0077E-01	-1.1625E+01	+1.0495E+03	-4.6803E+07	+1.6252E+06
bump2	+1.4010E-01	+3.1418E-03	+2.2184E-02	+3.3586E+00	+1.3501E+02	-1.0305E+07	-3.2505E+06
bump2a	+1.4001E-01	-3.0573E-03	-4.7571E-04	-1.6939E+00	+2.0138E+02	-1.0290E+07	-3.2505E+06
bump3	-6.9814E-02	-2.3173E-03	+1.0077E-01	-1.1625E+01	+1.0495E+03	-4.6803E+07	+1.6252E+06
New extraction bump magnets							
bump1	+7.5431E-02	-7.0906E-05	+4.5547E-02	+1.9956E-01	-8.1984E+00	-1.5063E+03	-3.5475E+05
bump2	-7.5431E-02	-7.8369E-05	+4.7016E-02	+1.3622E-01	-3.0061E+01	+1.2642E+03	+1.0748E+06
bump3	-7.5431E-02	+5.7844E-05	+4.8485E-02	+5.2060E-02	+8.1984E+00	-2.1518E+03	-5.6125E+05
bump4	+7.5431E-02	-9.3297E-07	+4.2608E-02	-5.3795E-02	+4.0992E+00	+1.4794E+04	-3.1769E+05

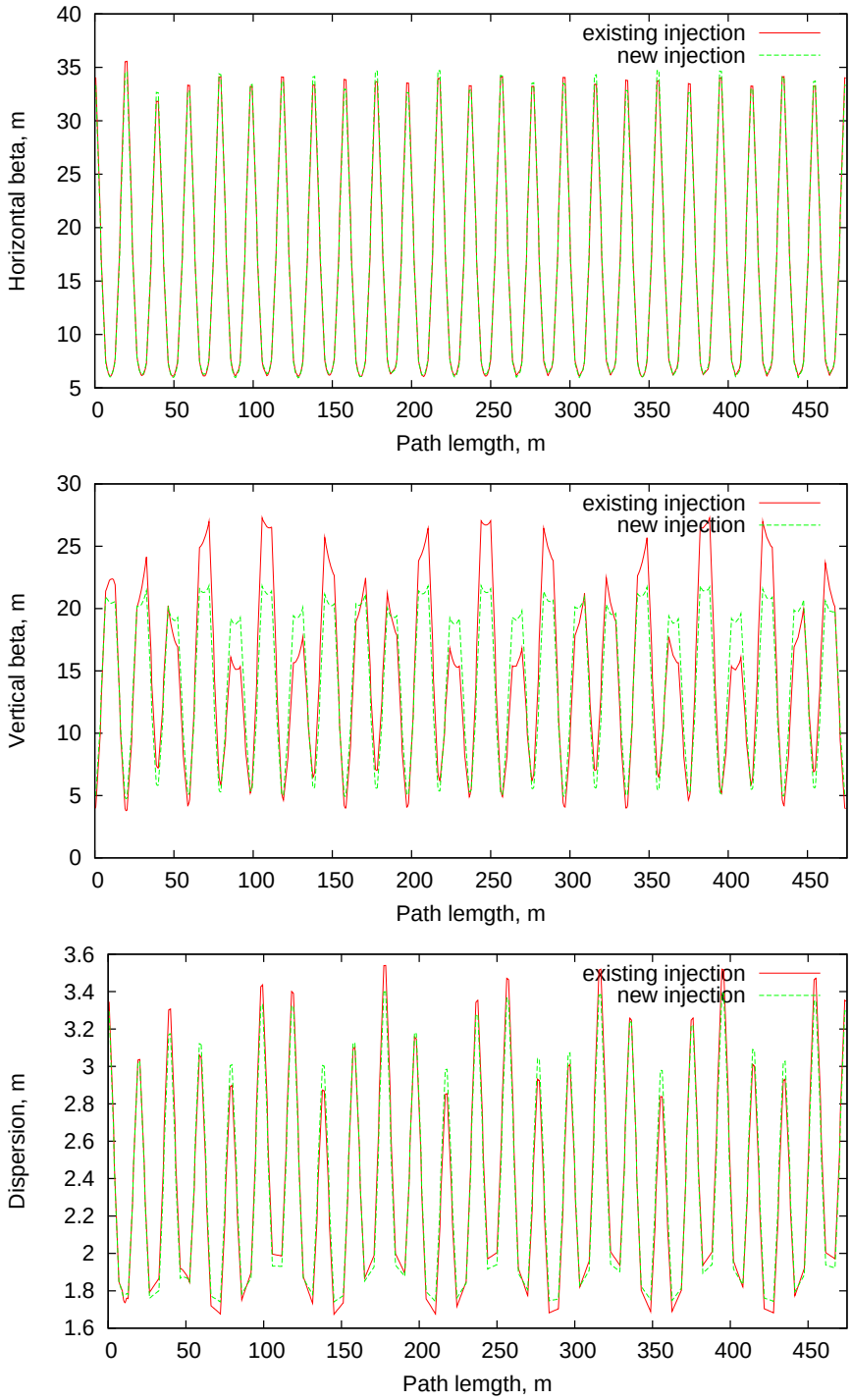

Figure 1: Fermilab Booster horizontal (top), vertical (middle) β functions and horizontal dispersion (bottom) at injection for new proposed and existing injection scheme. MAD calculations.

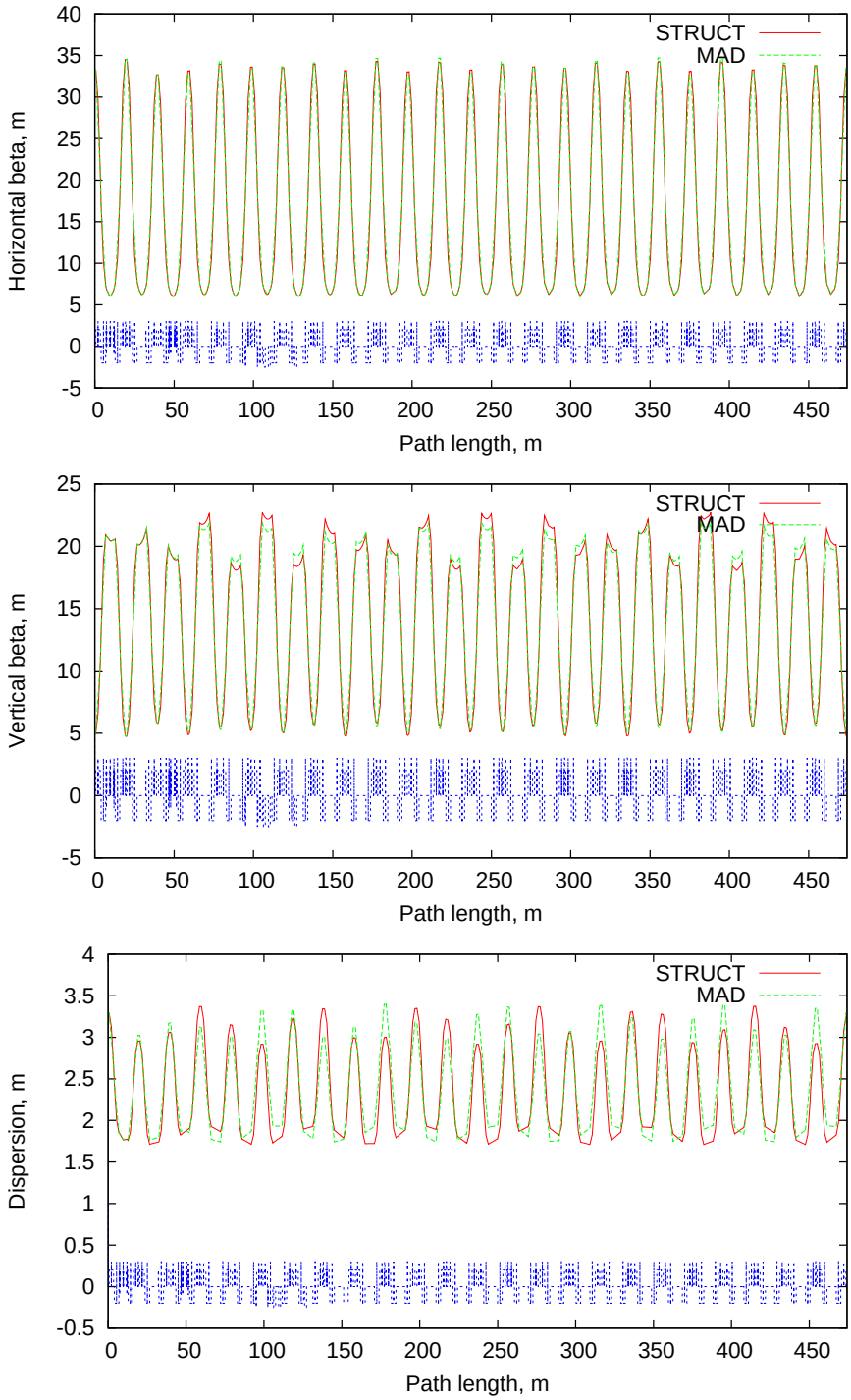

Figure 2: Fermilab Booster horizontal (top), vertical (middle) β functions and horizontal dispersion (bottom) at injection for new proposed injection scheme. MAD and STRUCT calculations.

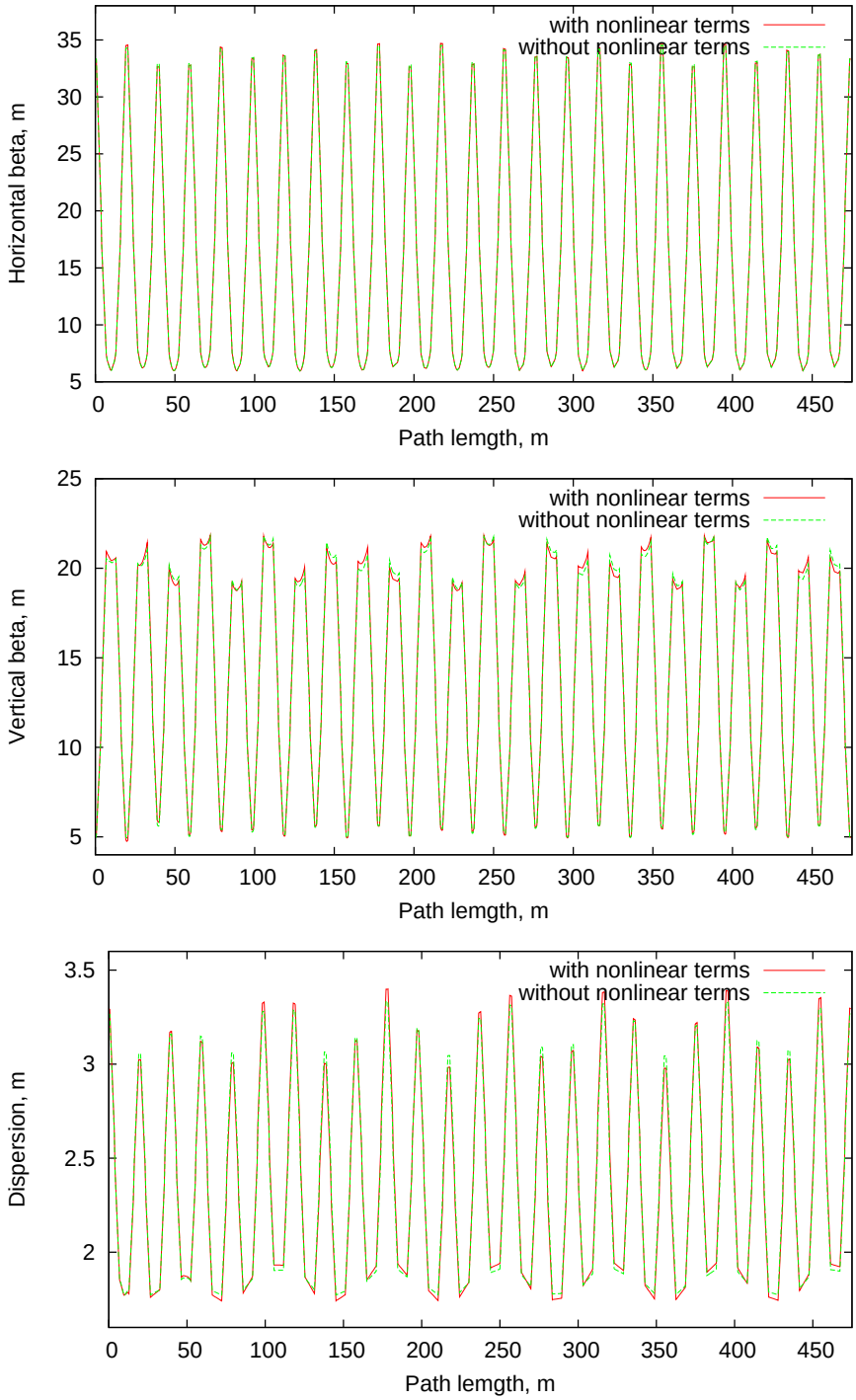

Figure 3: Fermilab Booster horizontal (top), vertical (middle) β functions and horizontal dispersion (bottom) at injection for new proposed injection scheme with and without nonlinear field harmonics. MAD calculations.

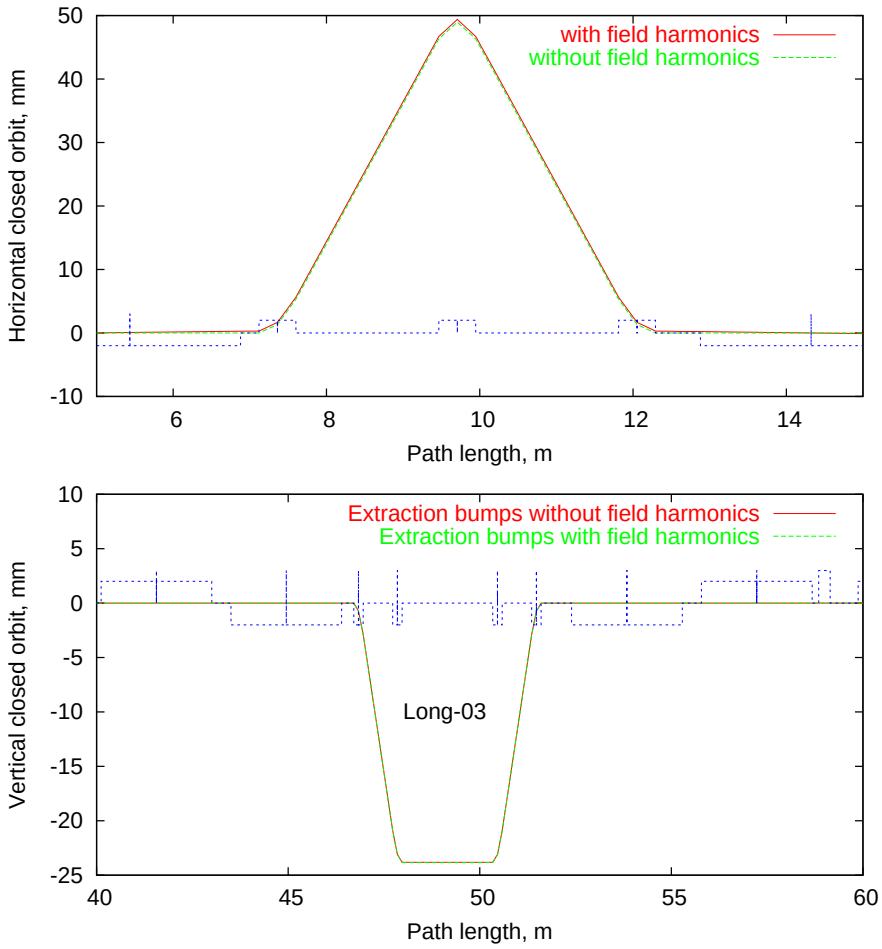

Figure 4: Horizontal (top) and vertical (bottom) closed orbit with ideal injection and extraction bump magnets and bump magnets with nonlinear field harmonics.

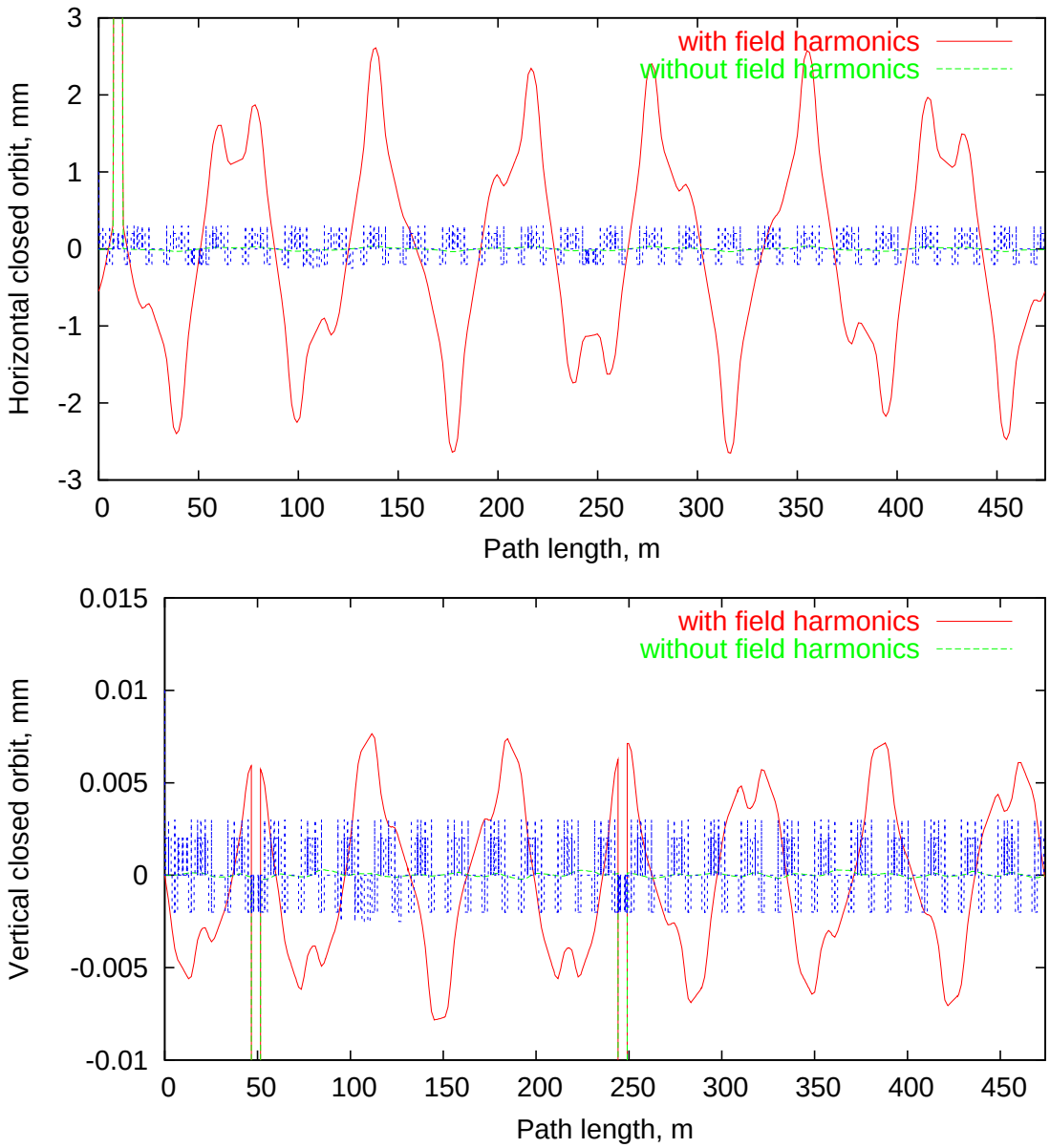

Figure 5: Horizontal (top) and vertical (bottom) closed orbit with ideal injection and extraction bump magnets and bump magnets with nonlinear field harmonics.

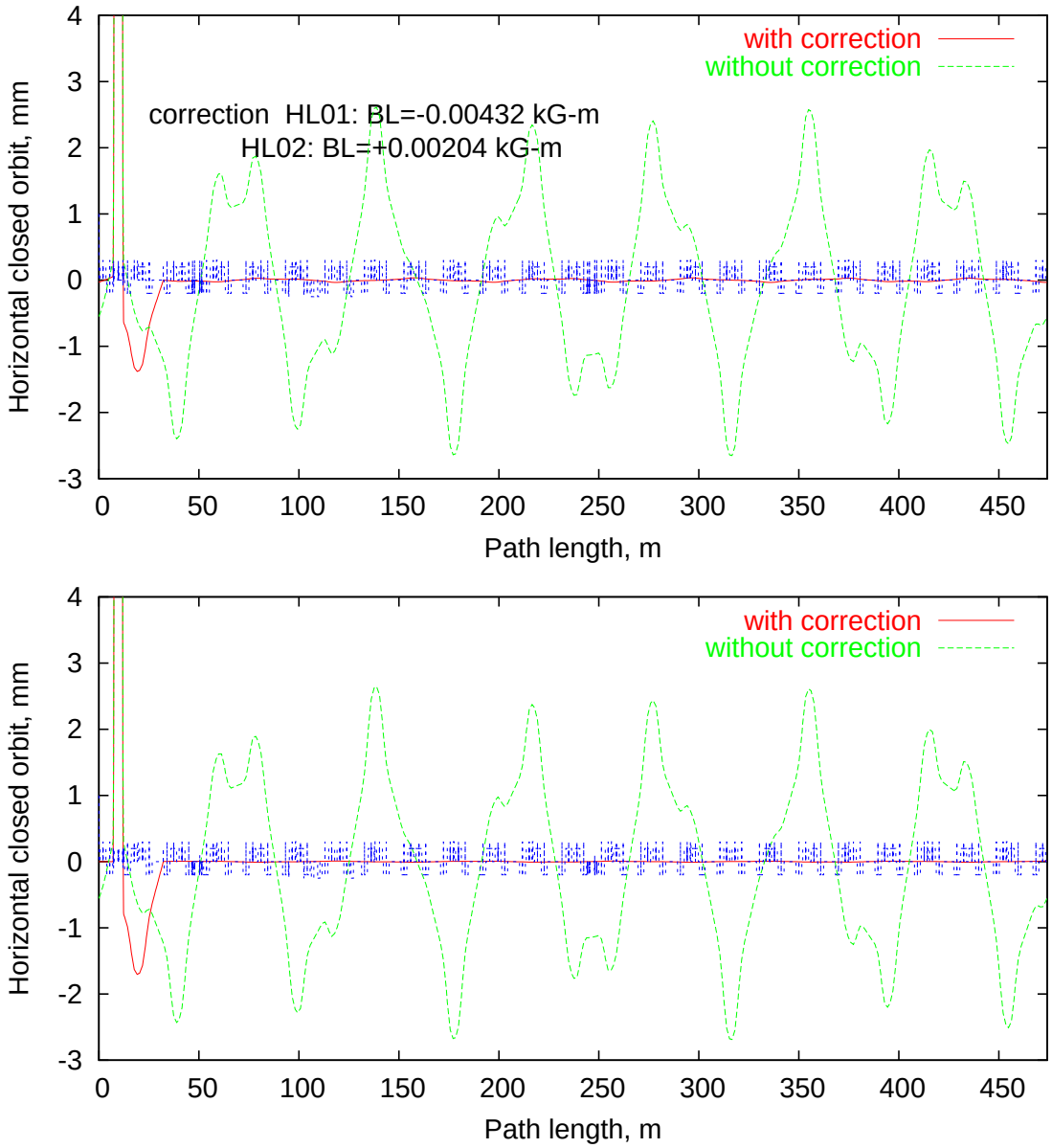

Figure 6: Top - horizontal closed orbit with extraction and injection bump magnets with nonlinear field harmonics with and without orbit correction. Orbit correction is performed by dipole corrector HL01 (BL=-0.00432 kG-m) and HL02 (BL=+0.00204 kG-m). Bottom - only quadrupole component is taken in the injection bump magnets.

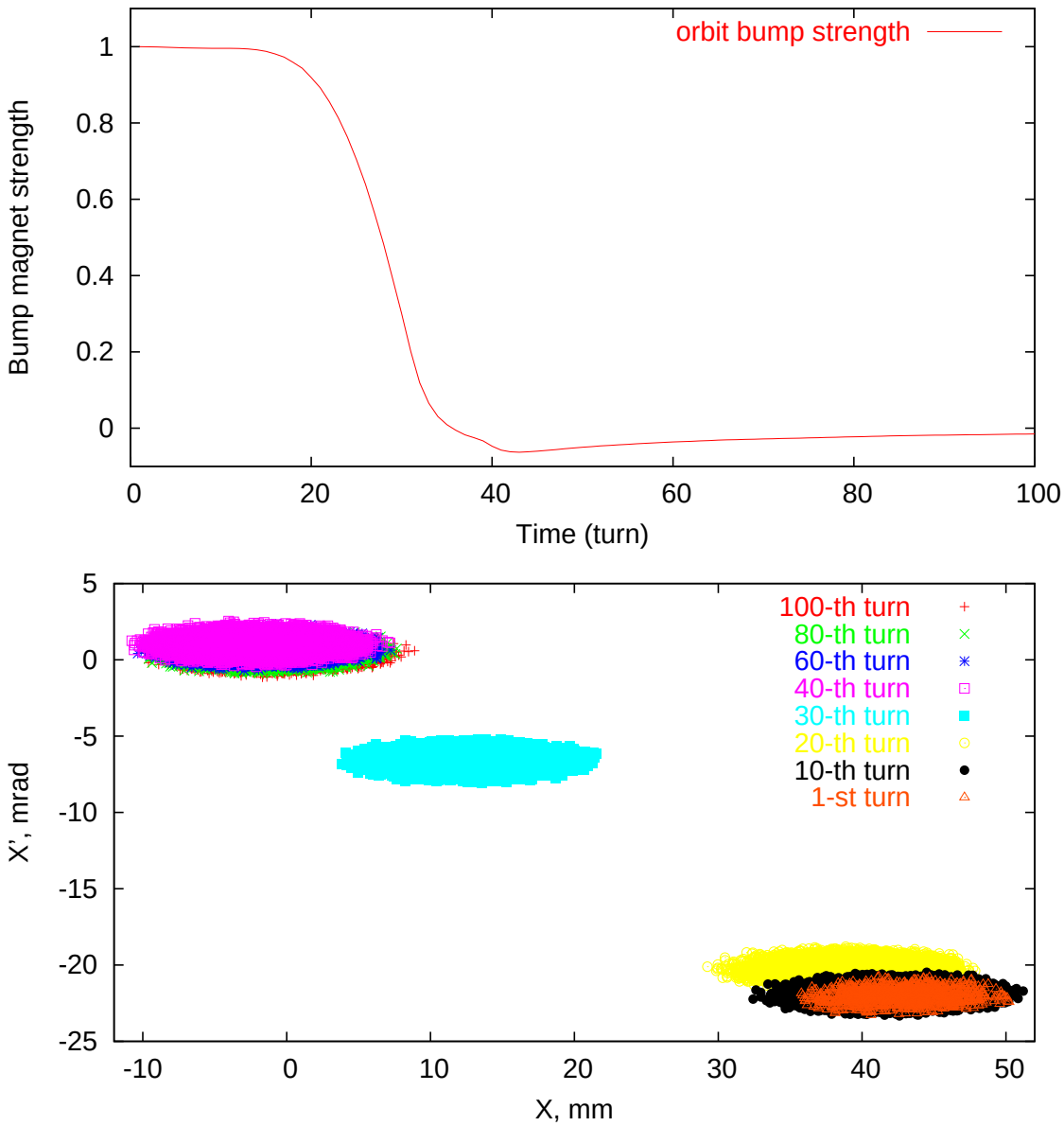

Figure 7: Orbit bump strength during injection (top) and circulating beam position (bottom) at turn No.1 (start of injection), No.10 (end of injection) and turns No.20, 30, 40, 60, 80 and 100 with nonlinear field harmonics in bump magnets.

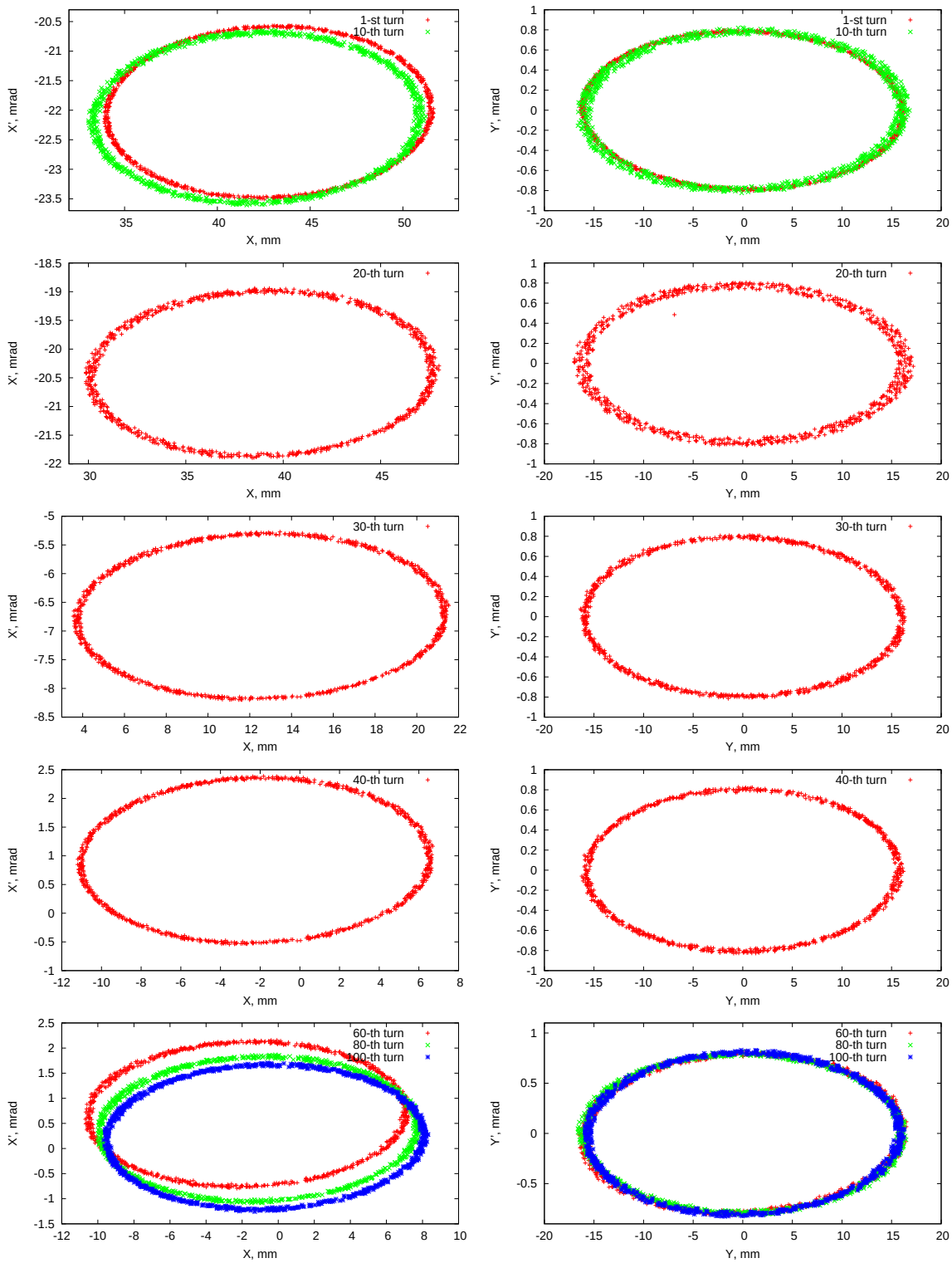

Figure 8: $3-\sigma_x$ (left) and $3-\sigma_y$ (right) ellipses of circulating beam injected at the first turn of injection are shown at turn No.1, 10, 20, 30, 40, 60, 80 and 100 with nonlinear field harmonics in bump magnets. Each particle has both horizontal and vertical betatron amplitude of $3-\sigma_{x,y}$.

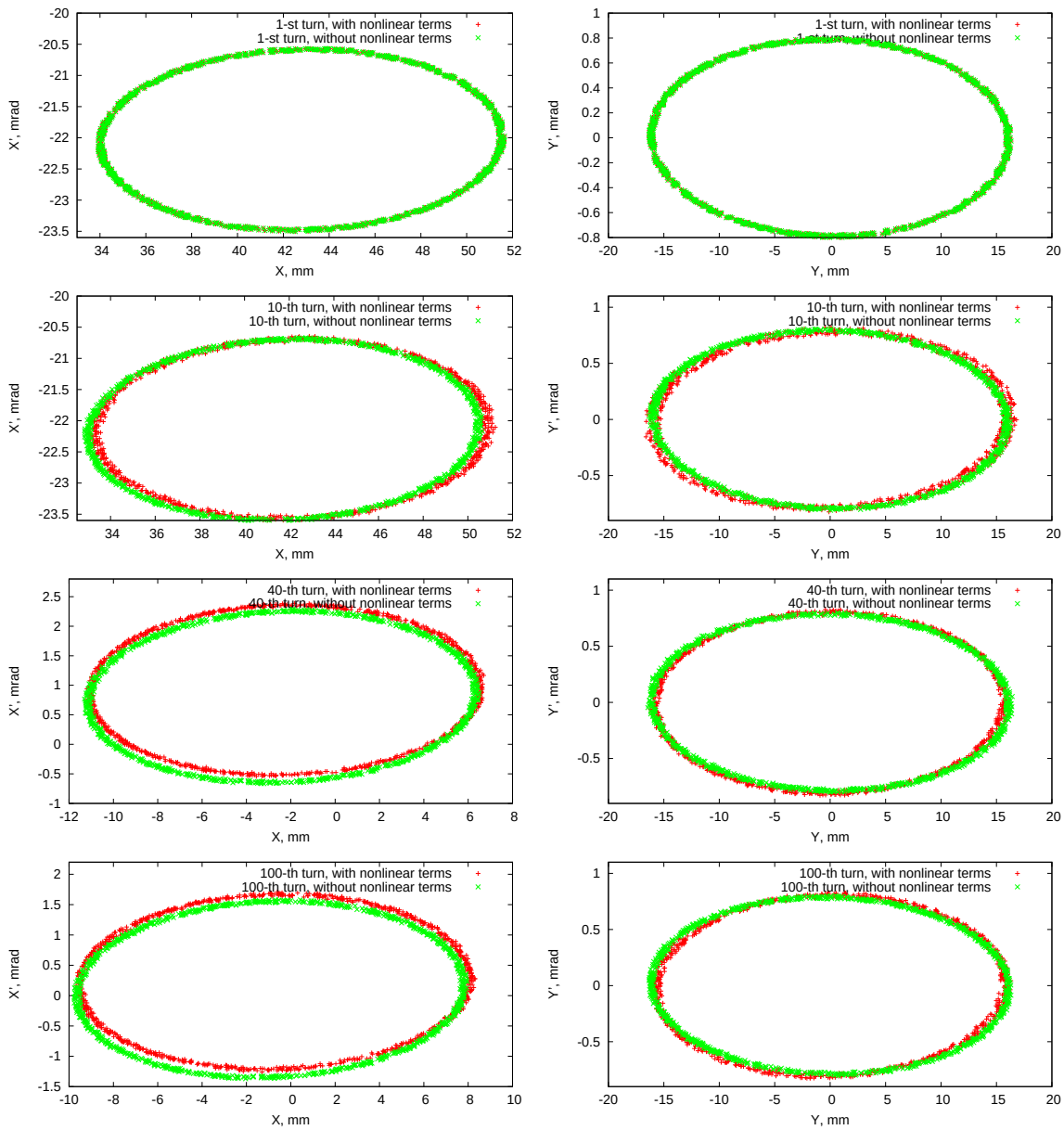

Figure 9: $3-\sigma_x$ (left) and $3-\sigma_y$ (right) ellipses of circulating beam at turns No.1, 10, 40 and 100 with and without nonlinear field harmonics in bump magnets.

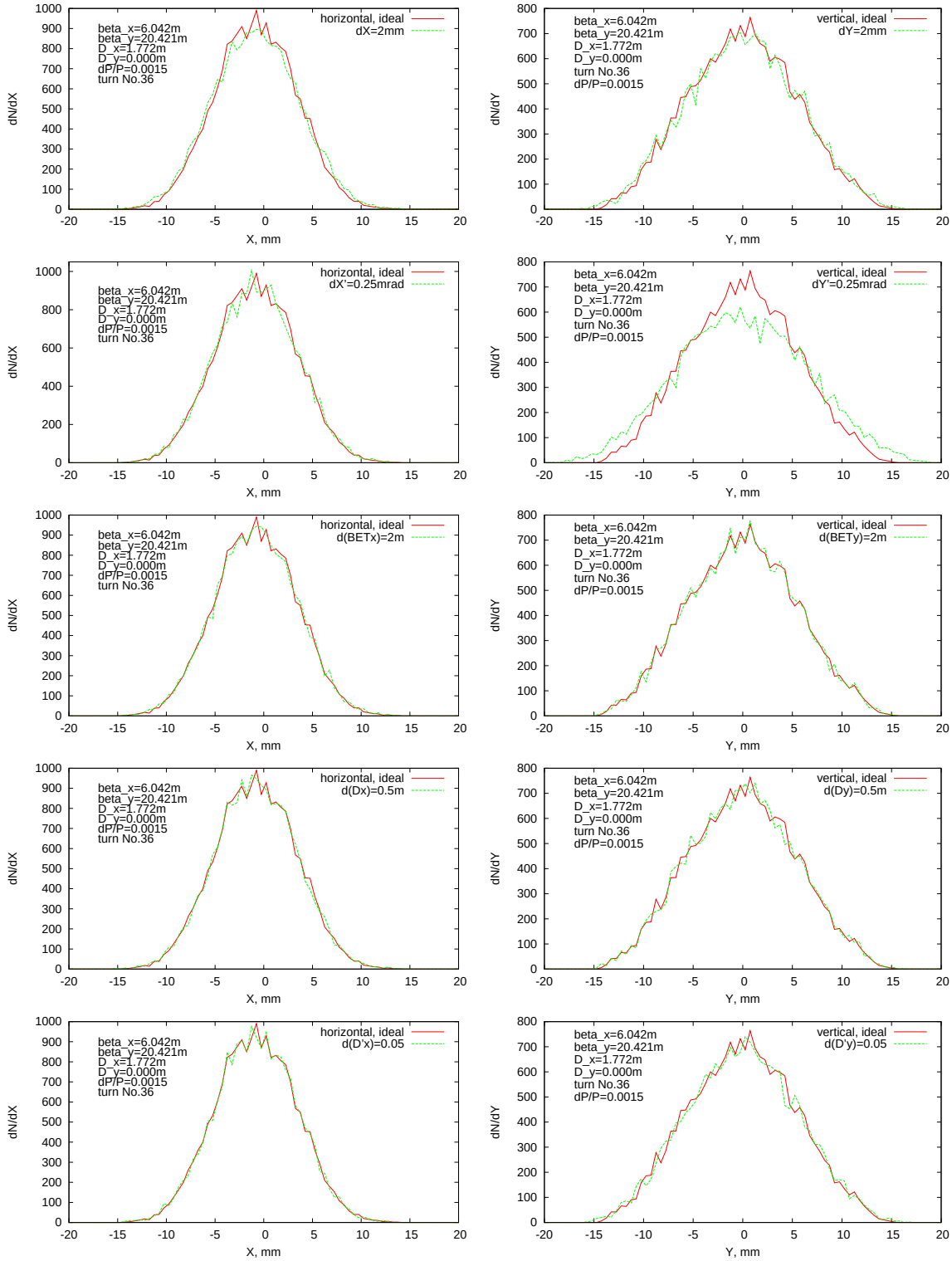

Figure 10: Effect of injected beam transverse and angular displacement by 2 mm and 0.25 mrad (first and second line)), mismatching of β-functions by 2 m (3-d line), dispersion by 0.5 m (4-th line) and angular dispersion by 0.05 (5-th line) in horizontal (left) and vertical (right) plane to the circulating beam after injection. Circulating beam size increase is of the order of 2 mm in horizontal plane and 4 mm in vertical plane from injected beam displacement by 2 mm; 2 mm in horizontal plane and 10 mm in vertical plane from angular displacement by 0.25 mrad; 2 mm in both planes from dispersion mismatch by 0.5 m and 2-3 mm from angular dispersion mismatch by 0.05 and mismatch of $\beta_{x,y}$ by 2 m effects beam size increase by $\sim$ 1 mm.

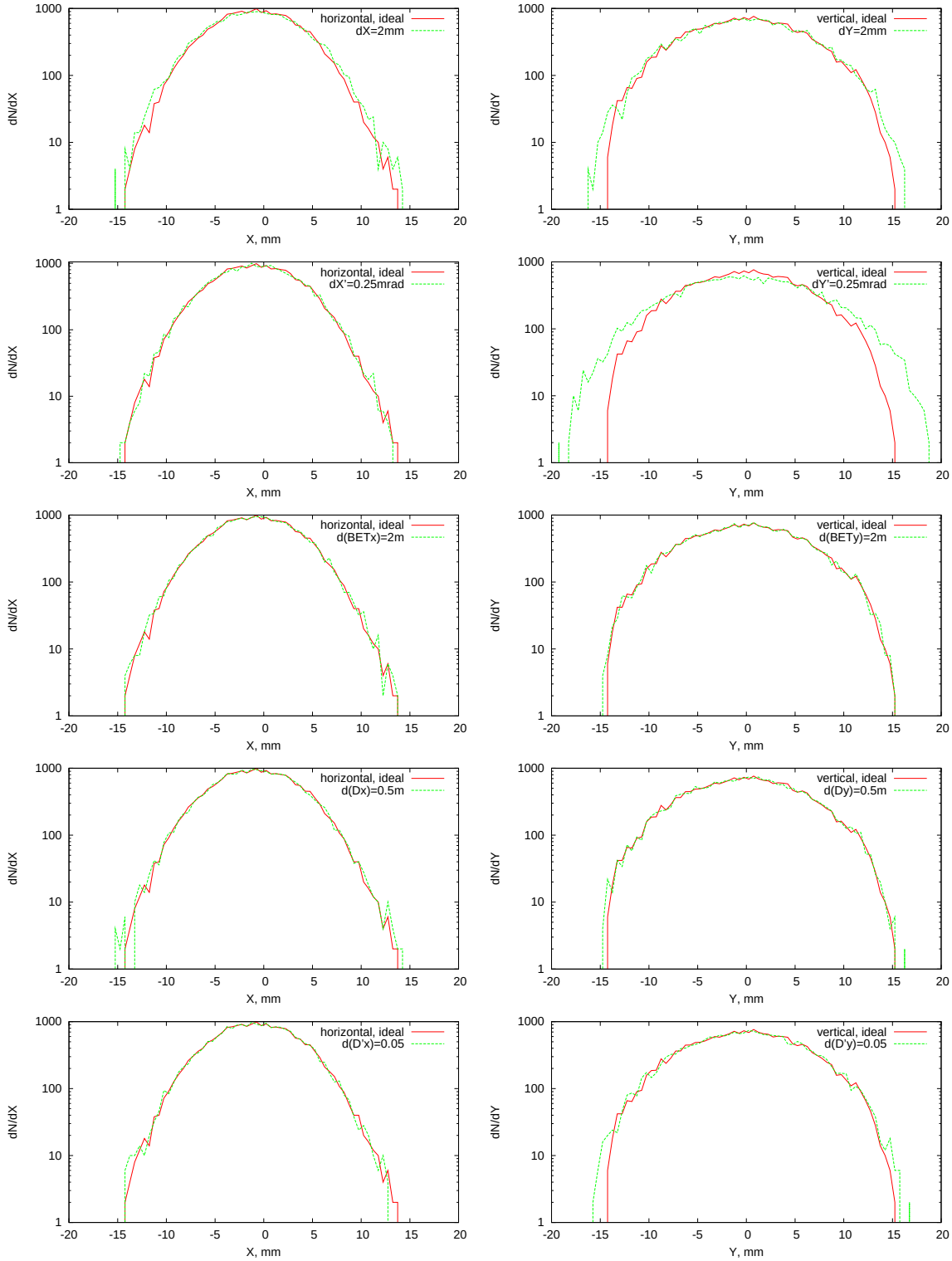

Figure 11: Effect of injected beam transverse and angular displacement by 2 mm and 0.25 mrad (first and second line)), mismatching of β-functions by 2 m (3-d line), dispersion by 0.5 m (4-th line) and angular dispersion by 0.05 (5-th line) in horizontal (left) and vertical (right) plane to the circulating beam after injection. Circulating beam size increase is of the order of 2 mm in horizontal plane and 4 mm in vertical plane from injected beam displacement by 2 mm; 2 mm in horizontal plane and 10 mm in vertical plane from angular displacement by 0.25 mrad; 2 mm in both planes from dispersion mismatch by 0.5 m and 2-3 mm from angular dispersion mismatch by 0.05 and mismatch of $\beta_{x,y}$ by 2 m effects beam size increase by $\sim$ 1 mm.