Simulation of Electron Lens Collimation in the Tevatron *

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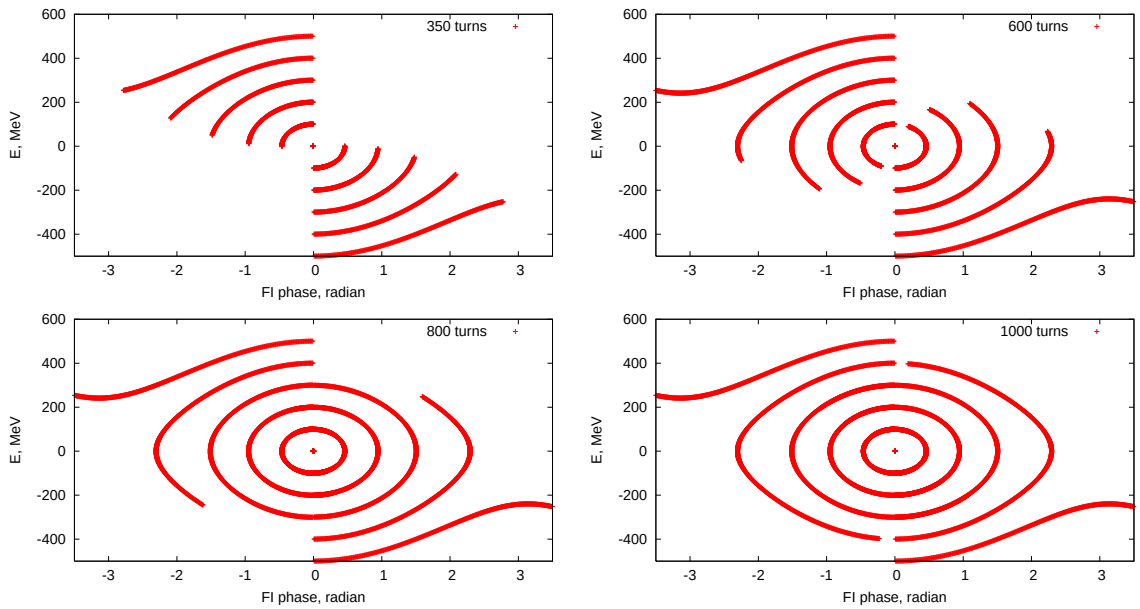

Figure 1: Longitudinal phase plane for 350, 600, 800 and 1000 turns at $U_{rf} = 1\ MV$. Eleven initial particles are taken at zero phase and different momentum to show difference in longitudinal oscillation tune for different amplitudes. The period of small amplitude particle is about 1400 turns, for particles with dP/p=4.e-04 it is 2100 turns.

*Work supported by the Universities Research Association, Inc., under contract DE-AC02-76CH00300 with the U. S. Department of Energy.

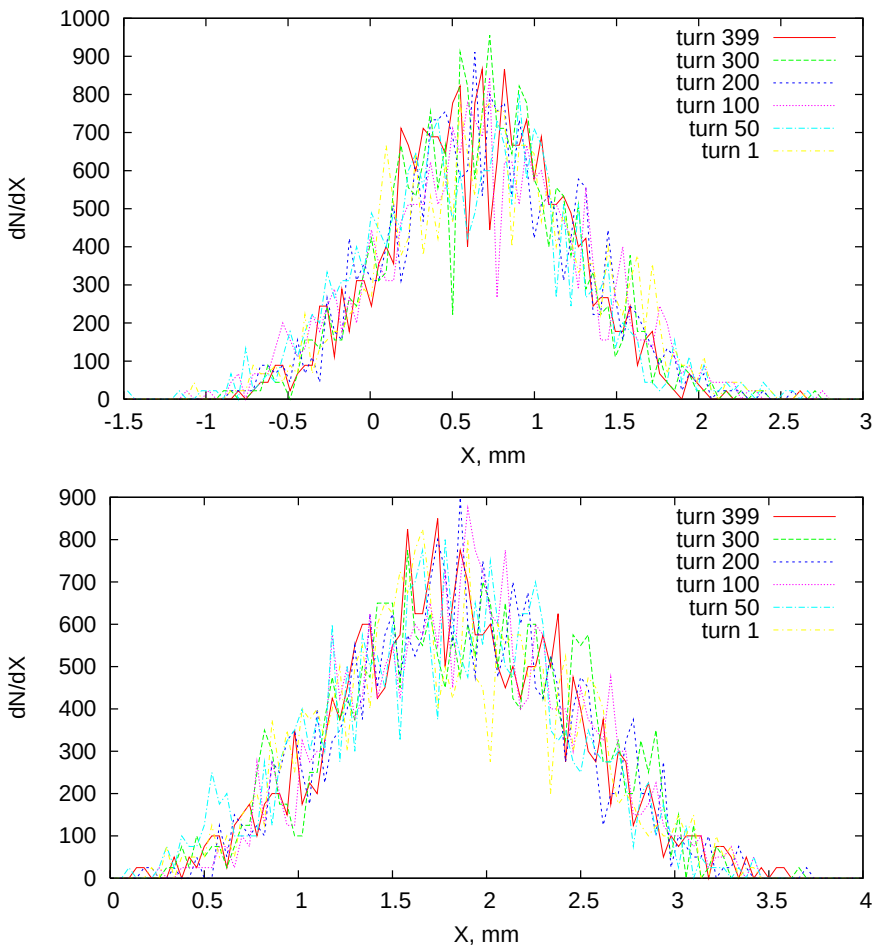

Figure 2: Horizontal (top) and vertical (bottom) 3σ beam profile in the RF cavity ($\beta_x = 55\ m$, $\beta_y = 105\ m$) during 400 turns without E-beam lens.

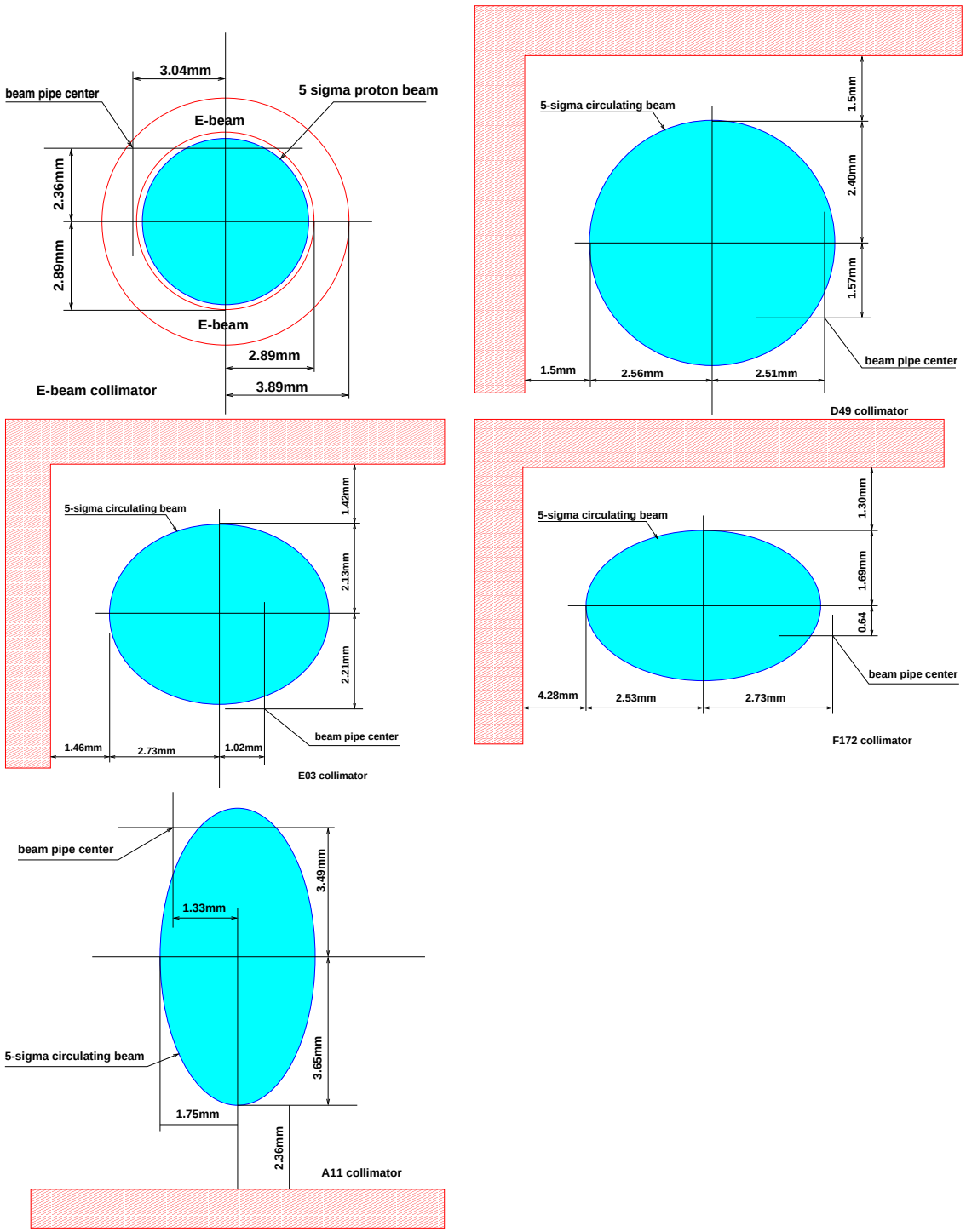

Figure 3: 5σ circulating beam position in the E-beam collimator, primary D49 and secondary E03, F172 and A11 collimators.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
2064.856	0.123E-02	2091	1.9975	25.00	38.10	2.5718	C49HESE
3109.904	0.475E+01	3187	14.9835	21.50	22.00	0.0050	colD49
3164.520	0.719E+00	3253	680.2689	21.00	22.00	1.5000	colE03
3197.194	0.407E-03	3295	1.5733	31.50	31.50	6.1214	BEND
3203.595	0.656E-03	3300	2.5363	31.50	31.50	6.1214	BEND
3206.493	0.353E-02	3310	0.9047	34.30	34.30	0.4064	DPACKU2
3213.272	0.501E-03	3314	1.9373	31.50	31.50	6.1214	BEND
3219.672	0.258E-03	3319	0.9986	31.50	31.50	6.1214	BEND
4407.219	0.316E-01	4516	29.9545	23.70	22.00	1.5000	coF172
5204.861	0.103E-01	5338	0.9985	34.30	34.30	0.1528	DR2TARG
5267.588	0.105E-01	5398	9.9890	20.00	20.00	1.5000	collA11

Table 1: Particle loss distribution along the accelerator at collimation. One thousand initial particles have horizontal amplitudes in the range of $A_x = (5-5.5)\sigma_x$ and vertical amplitudes of $A_y = (0.2-0.5)\sigma_y$. The hollow electron beam with hole of $R = 5\sigma_x$ and wall thickness of 1 mm is located at the middle of AØ with approximately equivalent $\beta_x = 108\ m$ and $\beta_y = 98\ m$. The E-beam current is modulated by a sinusoidal wave as [1+cos(2πω)] with period defined by betatron tune for $(5-6)\sigma$ particles. This period is a time during which particle in a betatron phase plane comes again approximately to its initial position. This period is equal to 12.45 turns for horizontal and 6.85 turns for vertical plane. So frequency of sinusoidal wave is $f_{revolution}/12.45 = 3.8\ kHz$ for horizontal and 7 kHz for vertical collimation. 85% of halo particles were collimated during 10,000 turns.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
21.974	0.189E-02	16	3.9944	34.30	34.30	3.3528	CB0Q2D
31.477	0.123E-02	30	1.9973	38.10	25.00	2.5718	B11VESE
2064.856	0.615E-03	2091	0.9984	25.00	38.10	2.5718	C49HESE
3109.904	0.950E+00	3187	2.9956	21.50	21.50	0.0050	colD49
3164.520	0.791E-01	3253	74.9056	21.00	21.00	1.5000	colE03
4407.219	0.843E-02	4516	7.9864	23.70	21.00	1.5000	coF172
5267.588	0.298E+00	5398	281.6898	20.00	20.00	1.5000	collA11
5291.759	0.409E-03	5423	1.5789	31.50	31.50	6.1214	BEND
5326.872	0.259E-03	5457	0.9990	31.50	31.50	6.1214	BEND
5337.413	0.258E-03	5472	0.9987	31.50	31.50	6.1214	BEND
5343.814	0.258E-03	5477	0.9975	31.50	31.50	6.1214	BEND
5356.616	0.257E-03	5487	0.9922	31.50	31.50	6.1214	BEND
6189.431	0.258E-03	6329	0.9981	31.50	31.50	6.1214	BEND
6223.390	0.633E-02	6372	1.9965	30.00	30.00	0.5000	dumpA48
6259.803	0.615E-03	6425	0.9987	38.10	25.00	2.5718	A49VESE
6265.446	0.541E-02	6436	2.9957	34.30	34.30	0.8763	DTRIPB

Table 2: Particle loss distribution along the accelerator at collimation. One thousand initial particles have horizontal amplitudes in the range of $A_x = (0.2-0.5)\sigma_x$ and vertical amplitudes of $A_y = (5-5.5)\sigma_y$. The hollow electron beam with hole of $R = 5\sigma_x$ and wall thickness of 1 mm is located at the middle of AØ with approximately equivalent $\beta_x = 108\ m$ and $\beta_y = 98\ m$. 39% of halo particles were collimated during 10,000 turns. It happens that at $(5-5.5)\sigma_y$ for initial particles in the E-lens, large number of particles is inside the E-beam hole because of β_y is a little less than β_x and $R_{hole} = 5\sigma_x$. At the next simulations I'll take initial particles with $A_x = (5.5-6)\sigma_x$ for horizontal collimation, and $A_y = (5.5-6)\sigma_y$ for vertical collimation. In this case all particles will be outside the E-beam hole.

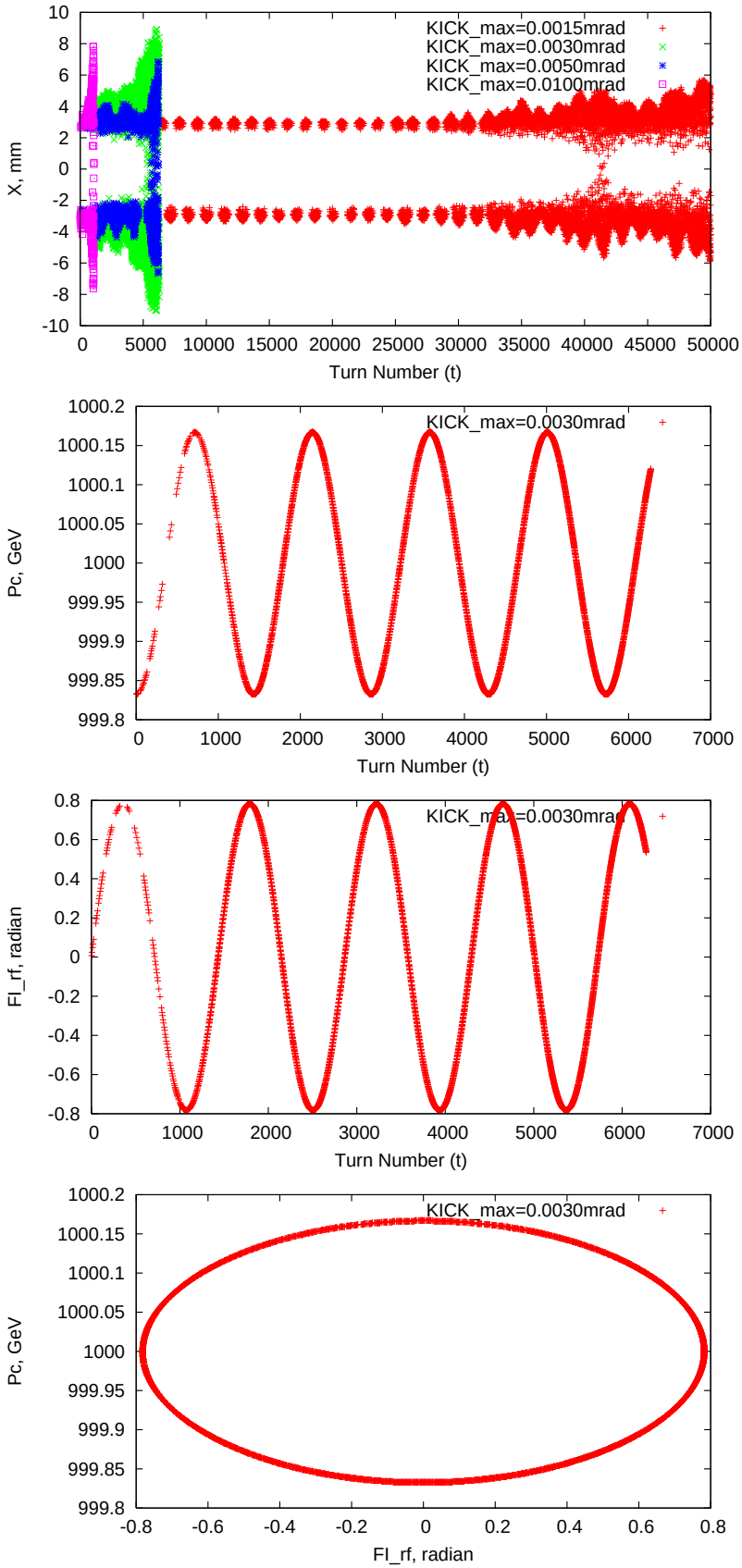

Figure 4: One randomly selected particle horizontal coordinate (top), momentum (second line), RF phase (third line) as a function of turn number at E-beam collimation in horizontal plane. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane. As shown on the top figure, particle is lost at the secondary collimator at turn No.1000 with E-beam lens strength of 0.01 mrad ($Kick_{max} = 0.01\ mrad$), at turn No.6000 with strength of 0.005 and 0.003 mrad and at turn No.50,000 with strength of 0.0015 mrad. 85% of halo particles were collimated during 10,000 turns with strength of 0.003 mrad.

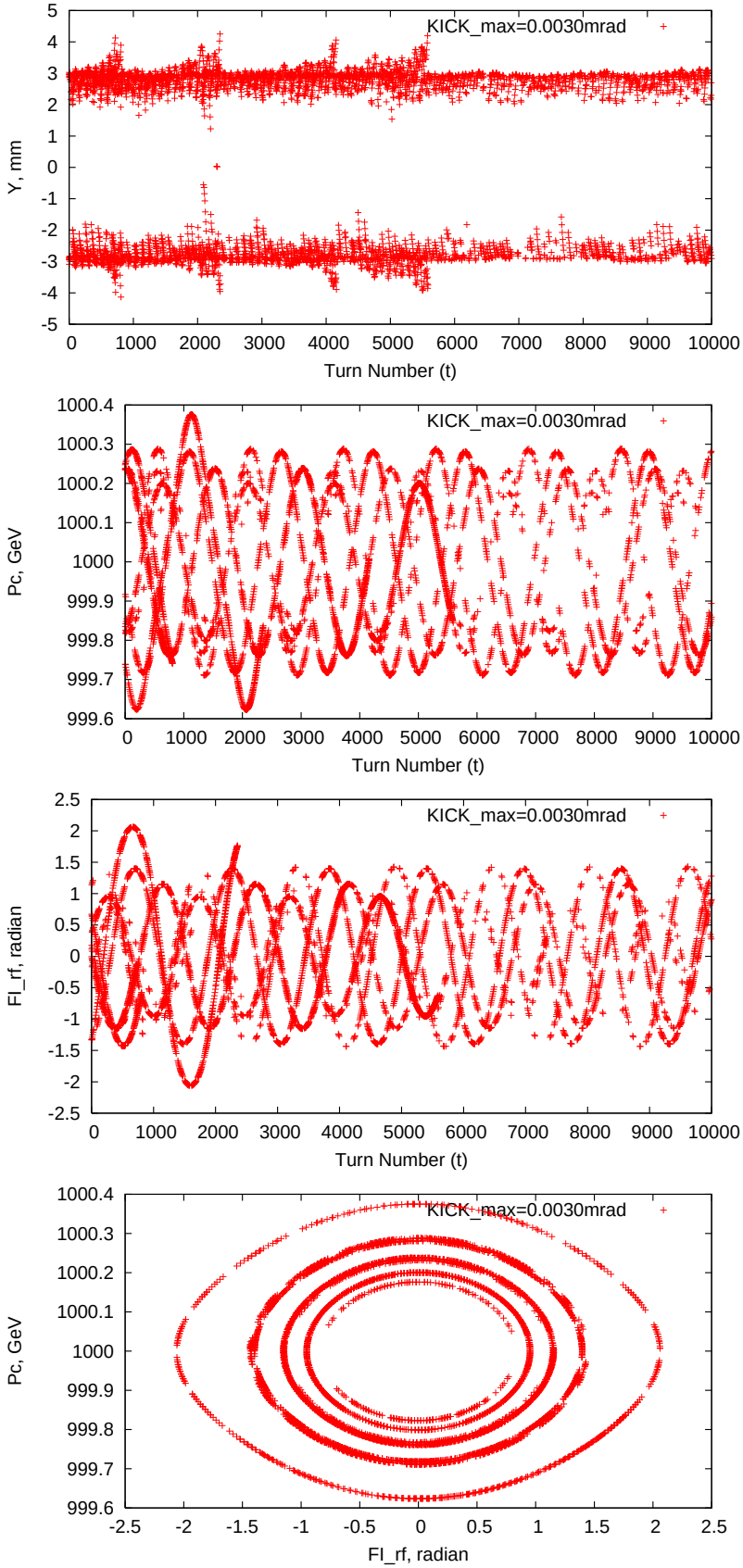

Figure 5: First 10 particle vertical coordinate (top), momentum (second line), RF phase (third line) as a function of turn number at E-beam collimation in vertical plane. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane. As shown on the top figure, 5 particles are lost at the secondary collimators during 5000 turns, but the rest 5 particles are not lost during 10,000 turns. 39.6% of halo particles were collimated during 10,000 turns with strength of 0.003 mrad.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
21.974	0.472E-03	16	0.9988	34.30	34.30	3.3528	CB0Q2D
31.477	0.615E-03	30	0.9987	38.10	25.00	2.5718	B11VESE
3109.904	0.380E+01	3187	11.9857	21.50	21.50	0.0050	colD49
3164.520	0.604E+00	3253	571.3654	21.00	21.00	1.5000	colE03
3203.595	0.219E-03	3300	0.8481	31.50	31.50	6.1214	BEND
3262.357	0.111E-01	3361	0.9828	34.30	34.30	0.1397	DBENDEN
4407.219	0.137E-01	4516	12.9818	23.70	21.00	1.5000	coF172
5267.588	0.163E+00	5398	153.8353	20.00	20.00	1.5000	collA11
5291.759	0.416E-03	5423	1.6067	31.50	31.50	6.1214	BEND
5386.359	0.257E-03	5517	0.9938	31.50	31.50	6.1214	BEND
6223.390	0.949E-02	6372	2.9944	30.00	30.00	0.5000	dumpA48
6254.285	0.185E-02	6421	2.9958	25.00	38.10	2.5718	A49HESE
6257.044	0.246E-02	6423	3.9948	38.10	25.00	2.5718	A49VESE
6264.569	0.472E-03	6435	0.9981	34.30	34.30	3.3528	CB0Q2F

Table 3: Particle loss distribution along the accelerator at collimation. One thousand initial particles have horizontal amplitudes in the range of $A_x = (5.5-6)\sigma_x$ and vertical amplitudes of $A_y = (0.2-0.5)\sigma_y$. The hollow electron beam with hole of $R = 5\sigma_x$ and wall thickness of 1 mm is located at the middle of AØ with approximately equivalent $\beta_x = 108\ m$ and $\beta_y = 98\ m$. 76.9% of halo particles were collimated during 10,000 turns. In this case we started calculations from $A_x = (5.5-6)\sigma_x$. This is by $0.5\sigma_x$ bigger than internal radius of the E-beam, and particles get less accumulated kick compared to the previous case where we started from $A_x = (5-5.5)\sigma_x$. Because of this number of collimated particles is a little less compared to previous case.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
31.477	0.799E-02	30	12.9804	38.10	25.00	2.5718	B11VESE
2064.856	0.246E-02	2091	3.9943	25.00	38.10	2.5718	C49HESE
3109.904	0.158E+01	3187	4.9927	21.50	21.50	0.0050	colD49
3164.520	0.178E+00	3253	168.7849	21.00	21.00	1.5000	colE03
3226.073	0.258E-03	3324	0.9980	31.50	31.50	6.1214	BEND
4407.219	0.116E-01	4516	10.9810	23.70	21.00	1.5000	coF172
5267.588	0.674E+00	5398	636.3112	20.00	20.00	1.5000	collA11
5285.358	0.192E-03	5418	0.7429	31.50	31.50	6.1214	BEND
5291.759	0.127E-02	5423	4.8901	31.50	31.50	6.1214	BEND
5298.160	0.239E-03	5428	0.9234	31.50	31.50	6.1214	BEND
5301.409	0.288E-02	5439	0.9413	34.30	34.30	0.5175	DPACKOU
5314.071	0.742E-03	5447	2.8659	31.50	31.50	6.1214	BEND
5320.471	0.771E-03	5452	2.9797	31.50	31.50	6.1214	BEND
5320.611	0.112E-01	5454	0.9894	34.30	34.30	0.1397	DBENDEN
5326.872	0.253E-03	5457	0.9782	31.50	31.50	6.1214	BEND
5337.413	0.511E-03	5472	1.9752	31.50	31.50	6.1214	BEND
6189.431	0.517E-03	6329	1.9963	31.50	31.50	6.1214	BEND
6223.390	0.474E-01	6372	14.9771	30.00	30.00	0.5000	dumpA48
6241.287	0.113E-01	6402	0.9986	34.30	34.30	0.1397	DBENDEN
6247.548	0.103E-02	6405	3.9943	31.50	31.50	6.1214	BEND
6250.964	0.102E-01	6415	0.9986	34.30	34.30	0.1556	DLB1
6254.285	0.615E-03	6421	0.9985	25.00	38.10	2.5718	A49HESE
6257.044	0.369E-02	6423	5.9907	38.10	25.00	2.5718	A49VESE
6259.803	0.615E-03	6425	0.9987	38.10	25.00	2.5718	A49VESE
6265.446	0.361E-02	6436	1.9976	34.30	34.30	0.8763	DTRIPB

Table 4: Particle loss distribution along the accelerator at collimation. One thousand initial particles have horizontal amplitudes in the range of $A_x = (0.2 - 0.5)\sigma_x$ and vertical amplitudes of $A_y = (5.5 - 6)\sigma_y$. The hollow electron beam with hole of $R = 5\sigma_x$ and wall thickness of 1 mm is located at the middle of AØ with approximately equivalent $\beta_x = 108\ m$ and $\beta_y = 98\ m$. 89.2% of halo particles were collimated during 10,000 turns.

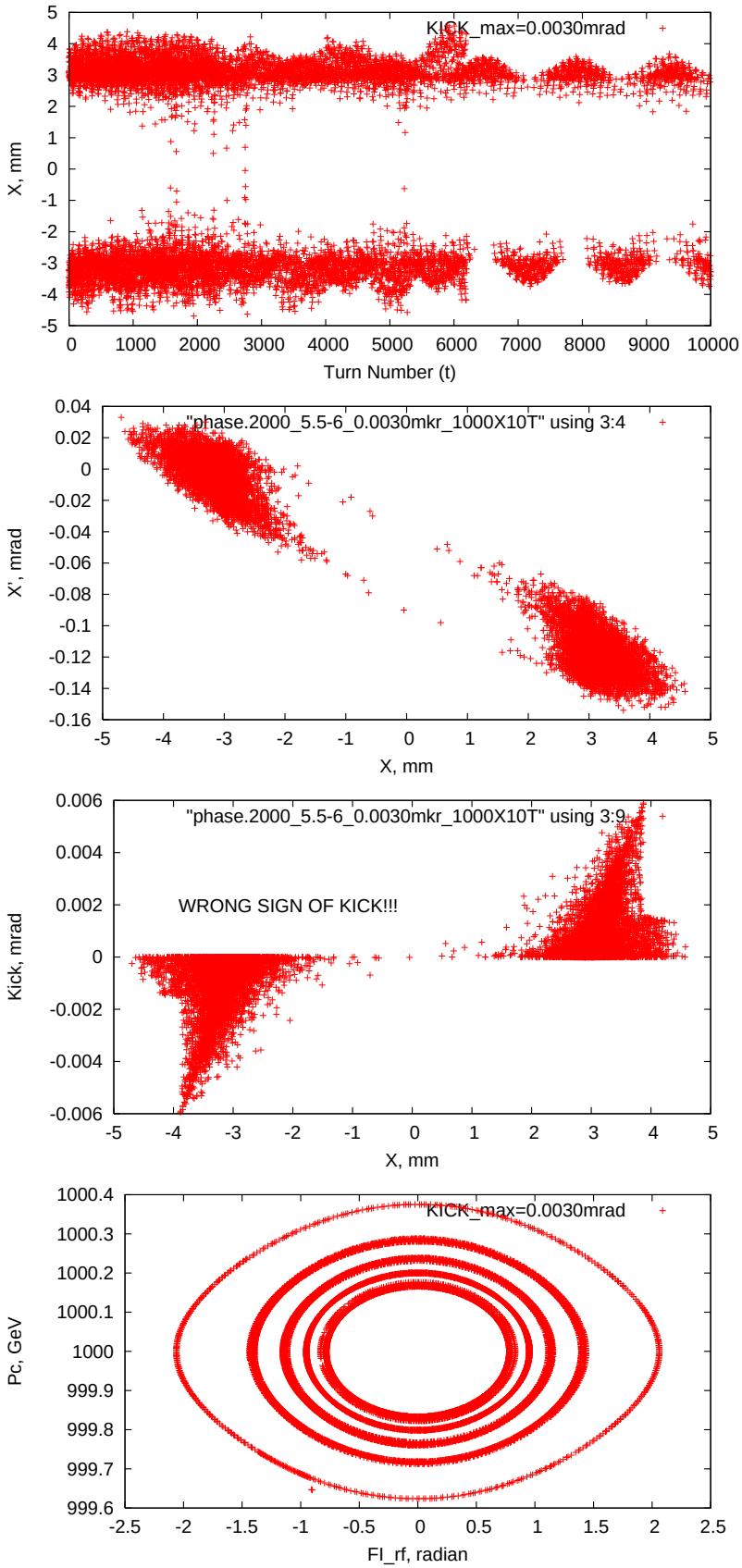

Figure 6: First 10 particle particle horizontal coordinate (top), betatron phase plane (second line), E-beam kick as a function of particle X coordinate (third line) as a function of turn number at E-beam collimation in horizontal plane. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane. 76.9% of halo particles were collimated during 10,000 turns with strength of 0.003 mrad. As shown on the second line figure, 8 particles are lost at the secondary collimators during 6000 turns, but the rest 2 particles are not lost during 10,000 turns.

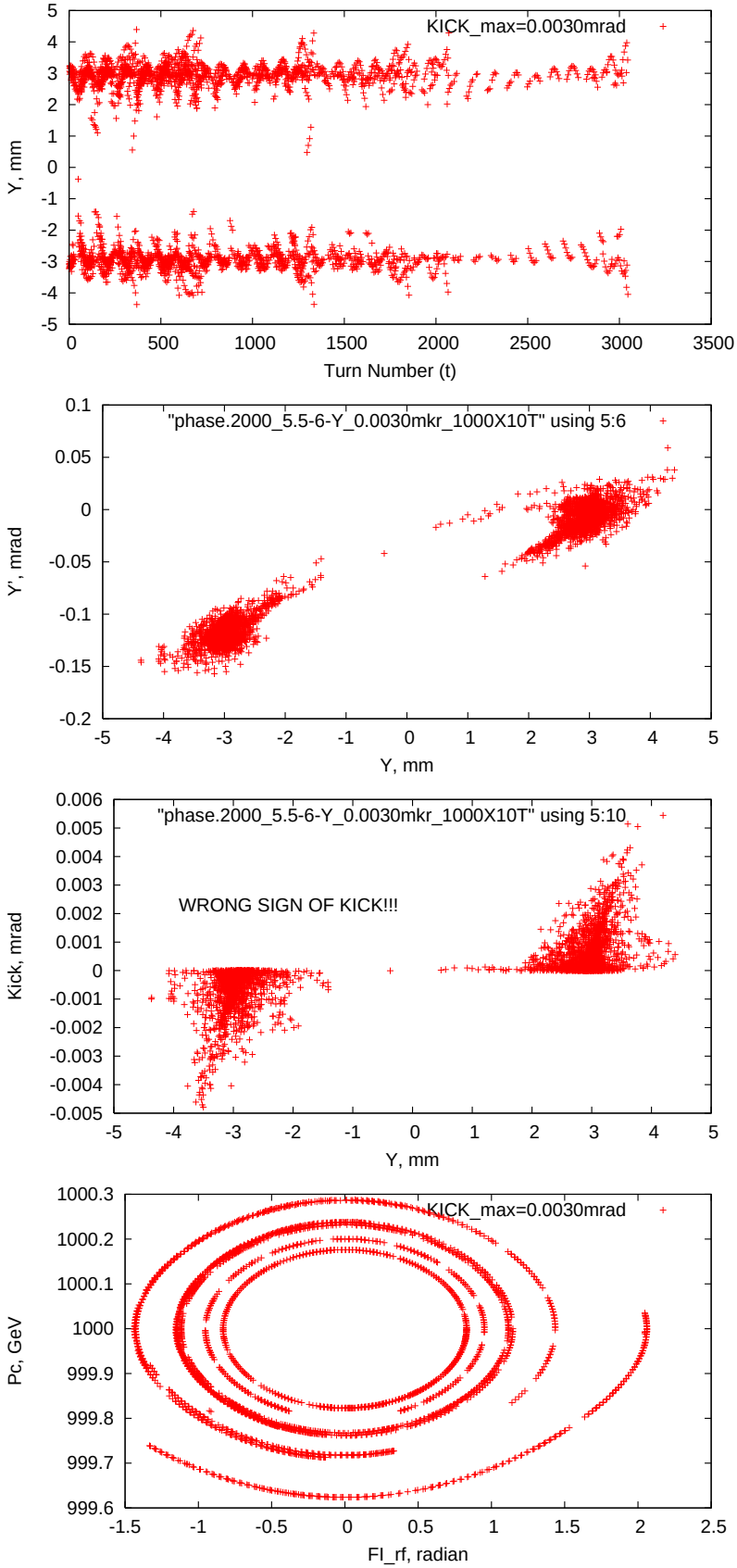

Figure 7: First 10 particle vertical coordinate (top), betatron phase plane (second line), E-beam kick as a function of particle Y coordinate (third line) as a function of turn number at E-beam collimation in vertical plane. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane. All 10 particles are lost during 3000 turns because betatron resonance period in vertical plane is 6.85 turns instead of 12.45 for horizontal plane. 89.2% of halo particles were collimated during 3500 turns with strength of 0.003 mrad. We started here from $A_y = (5.5-6)\sigma_y$ for vertical collimation.

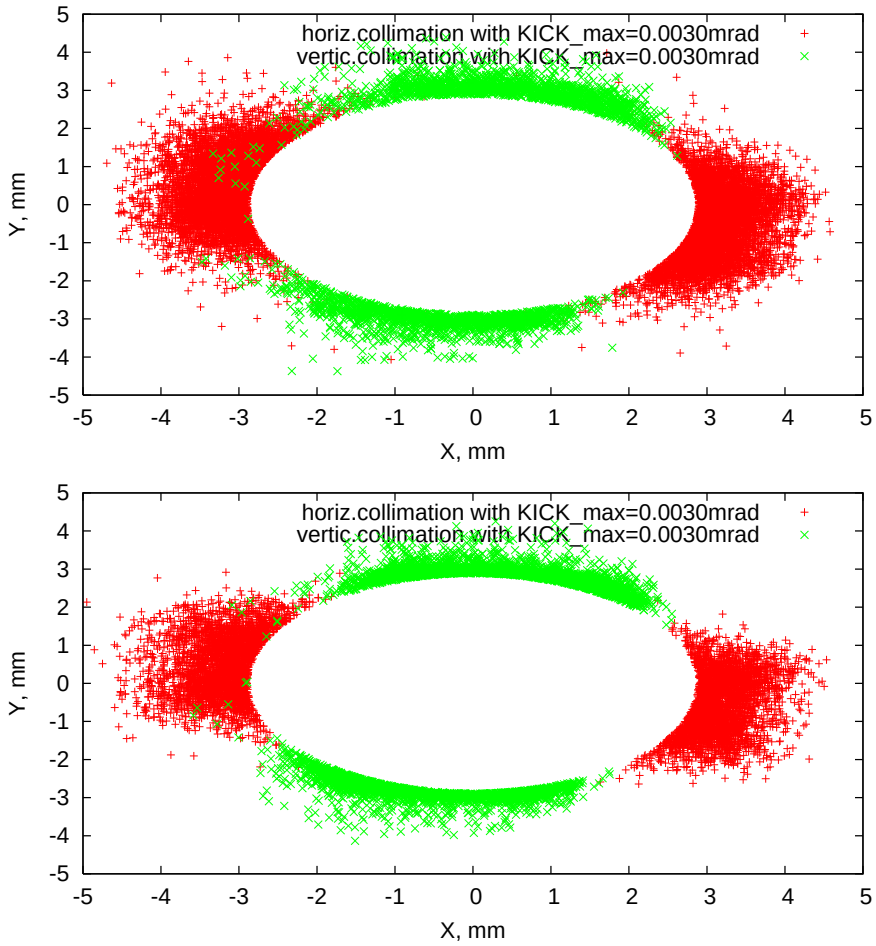

Figure 8: Beam size evolution in the E-lens during collimation (halo particles outside the $R = 5\sigma_x$ are shown). Top - for initial particles in the range of $A = (5-5.5)\sigma$, bottom - for initial particles in the range of $A = (5.5-6)\sigma$. It is better to start tracking from $A = (5-5.5)\sigma_x$ for horizontal collimation, and from $A = (5.5-6)\sigma_y$ for vertical collimation. Actually in a final simulations we need to start tracking from the beam with amplitudes which are less than internal radius of E-beam, and force the particle amplitude growth due to artificial beam-gas scattering. This will require wore time for calculations.

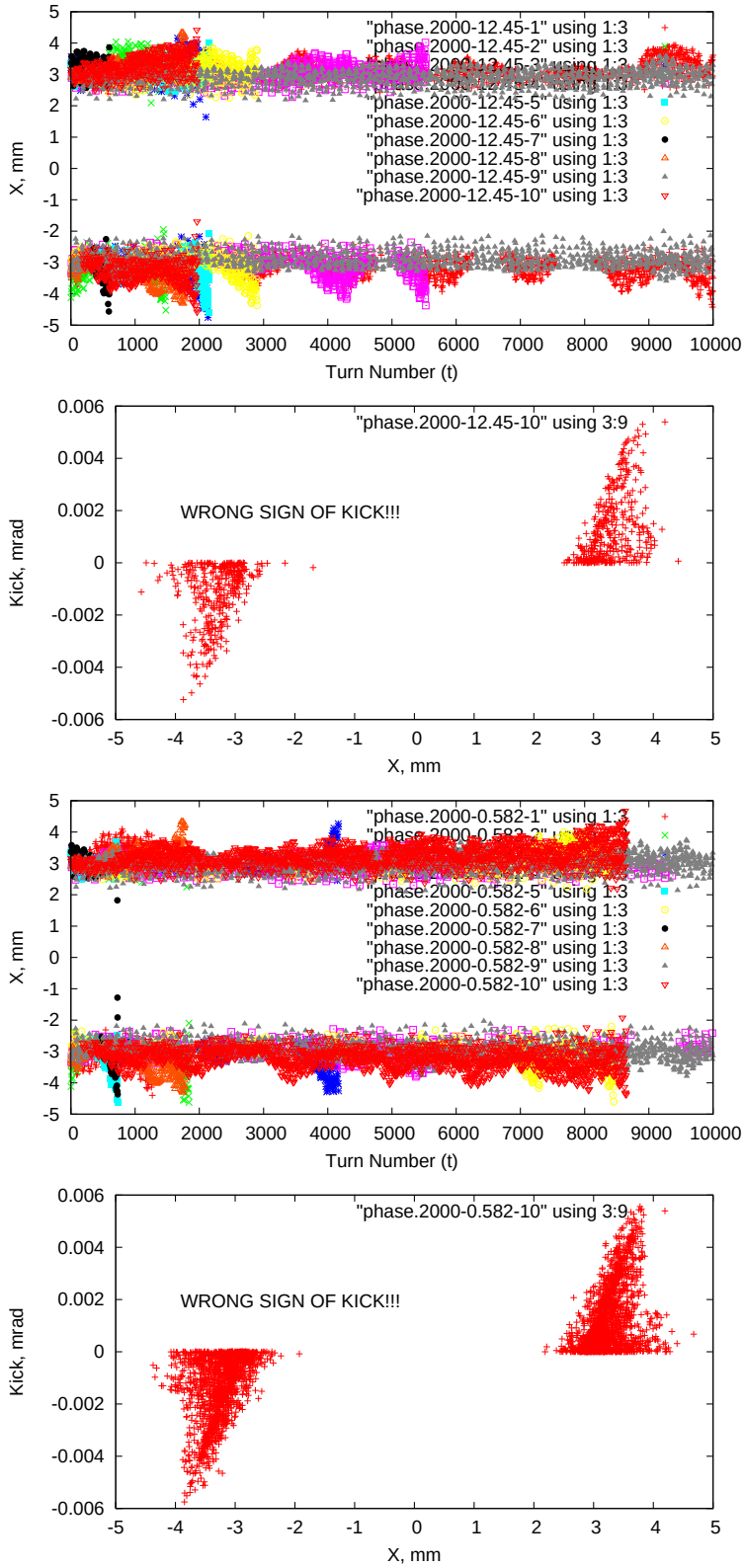

Figure 9: The E-beam current is modulated by a sinusoidal wave as [1+cos(2πω)] with period defined by betatron tune for $(5-6)\sigma$ particles. This period is a time during which particle in a betatron phase plane comes again approximately to its initial position. This period is equal to 12.45 turns for horizontal and 6.85 turns for vertical plane. So frequency of sinusoidal wave is $f_{revolution}/12.45 = 3.8\ kHz$ for horizontal and 7 kHz for vertical collimation. 10 particle horizontal coordinate and E-beam kick are shown on the top and second line for this case. On the third and bottom lines the phase of sinusoidal wave was changed by $0.582\times 2\pi$ during 1 turn. On average (from 10 particles), particle comes to the secondary collimator during 3855 turns with 12.45 turn period of sinusoidal wave and during 4762 turns with $0.582\times 2\pi$ phase change per turn.

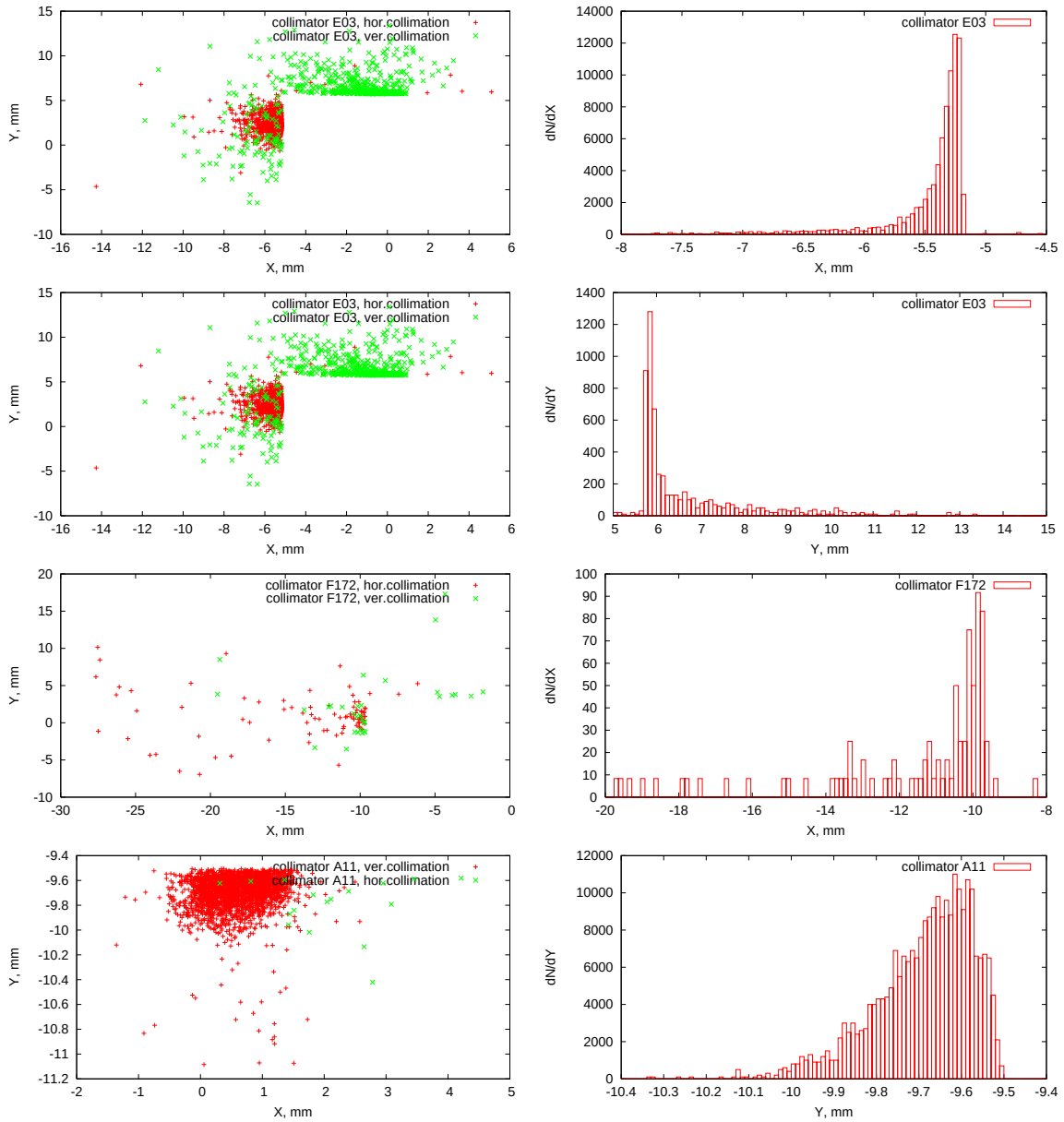

Figure 10: Beam population (left) and distribution (right) in the secondary collimators at collimation in a horizontal and vertical plane with E-beam lens strength of 0.0030 mrad.

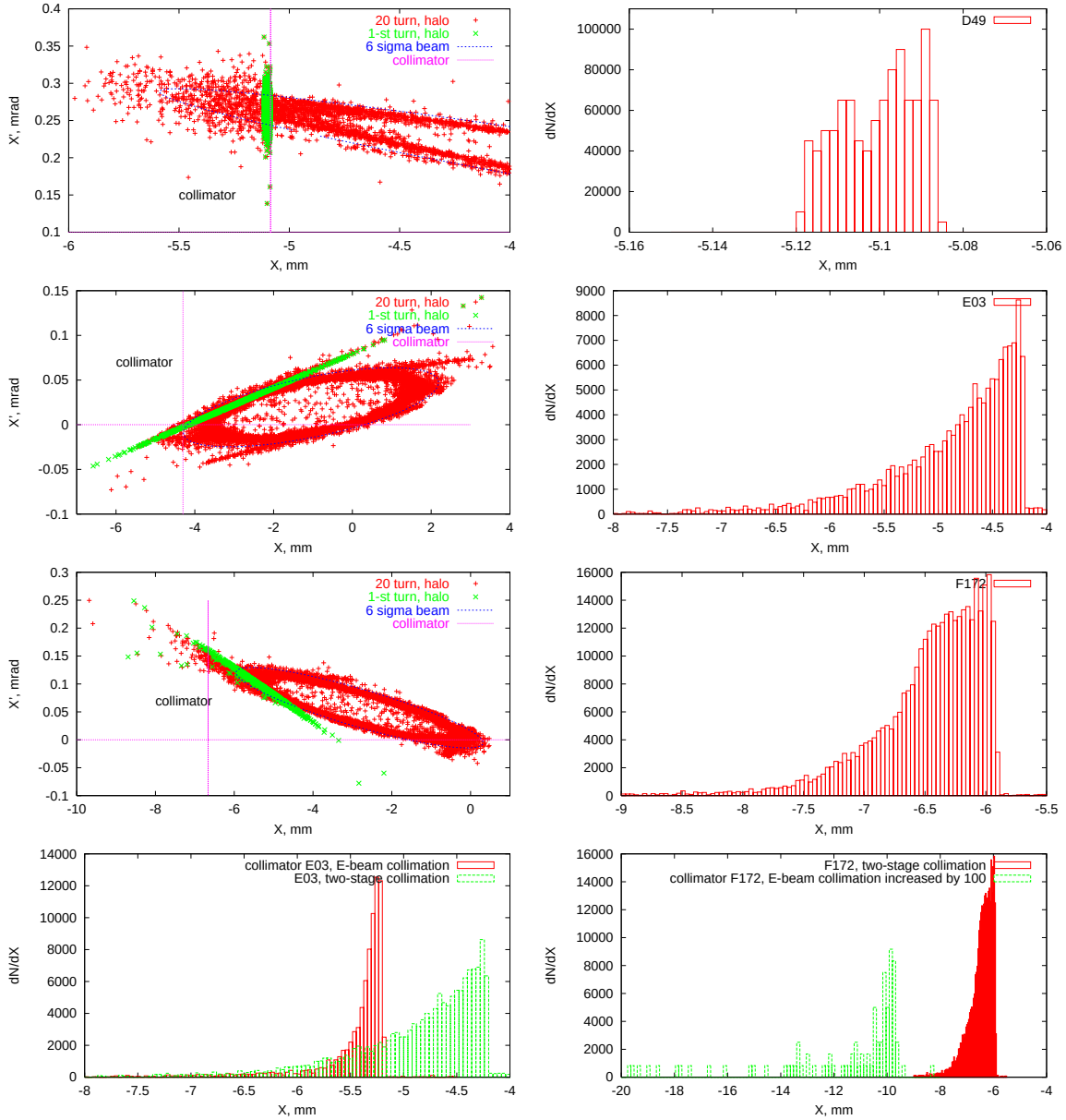

Figure 11: Horizontal phase space (left) and distribution (right) at primary proton collimator D49 (top), and secondary collimators E03 (second line) and F172 (third line) at two-stage collimation with 5 mm length tungsten primary collimator. Green - halo particles at the first turn after interaction with the primary collimator, red - secondary halo, blue - 6σ envelope. Bottom line shows comparison of particle distribution in the secondary collimators for two-stage and E-beam collimation. In both cases distribution is pretty good with respect to probability of particle out-scattering from the collimator jaws.

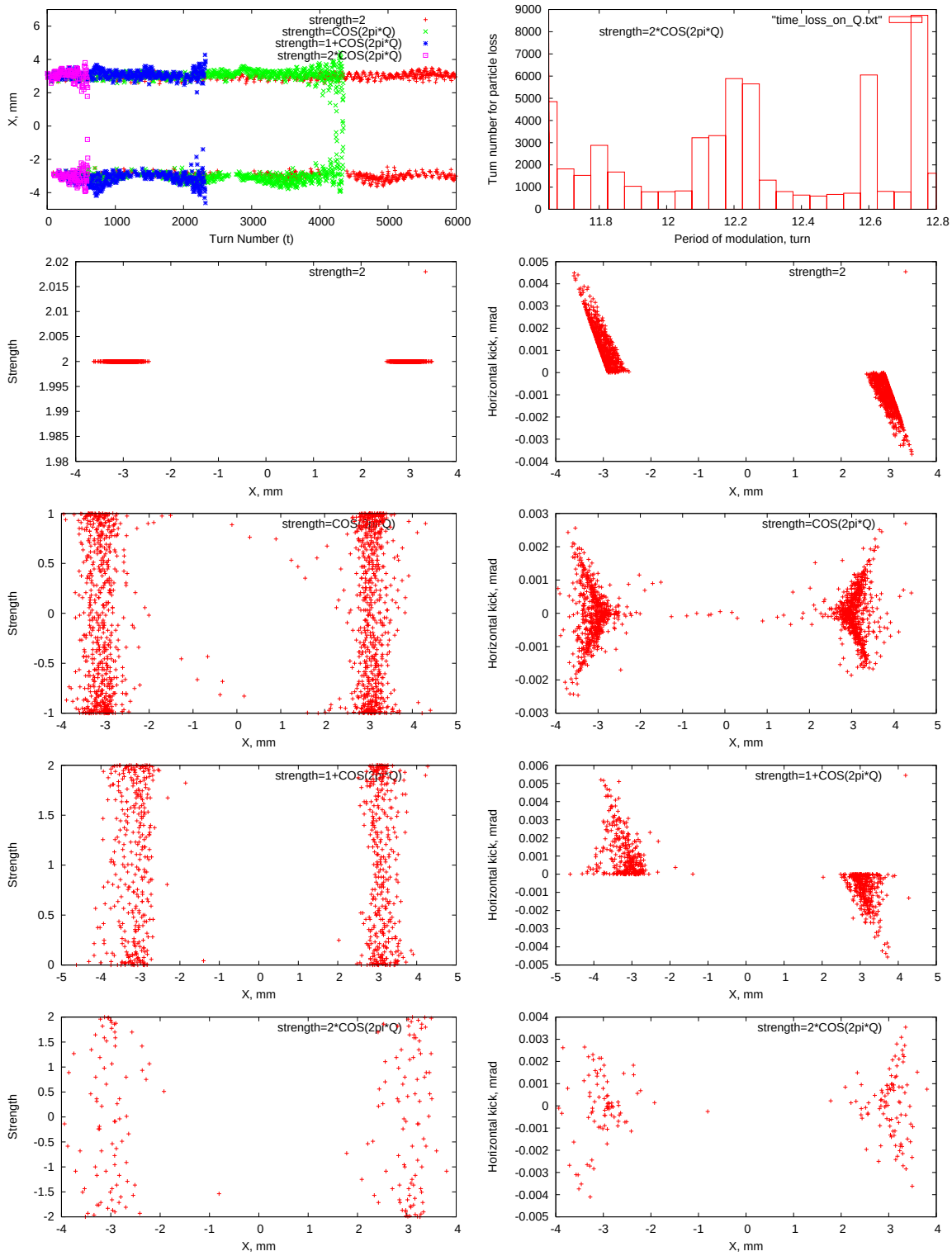

Figure 12: Particle horizontal coordinate as a function of turn number (top left) and turn number for particle loss as a function of period of E-lens strength modulation (top right). E-beam lens kick is defined by the particle position with respect to E-beam and by modulation of E-beam current. Part of the kick strength defined by current modulation is shown on the left, and the total kick is shown on the right for different function of modulation. There is no beam excitation without beam modulation. The effect of excitation depends on the amplitude of modulation.

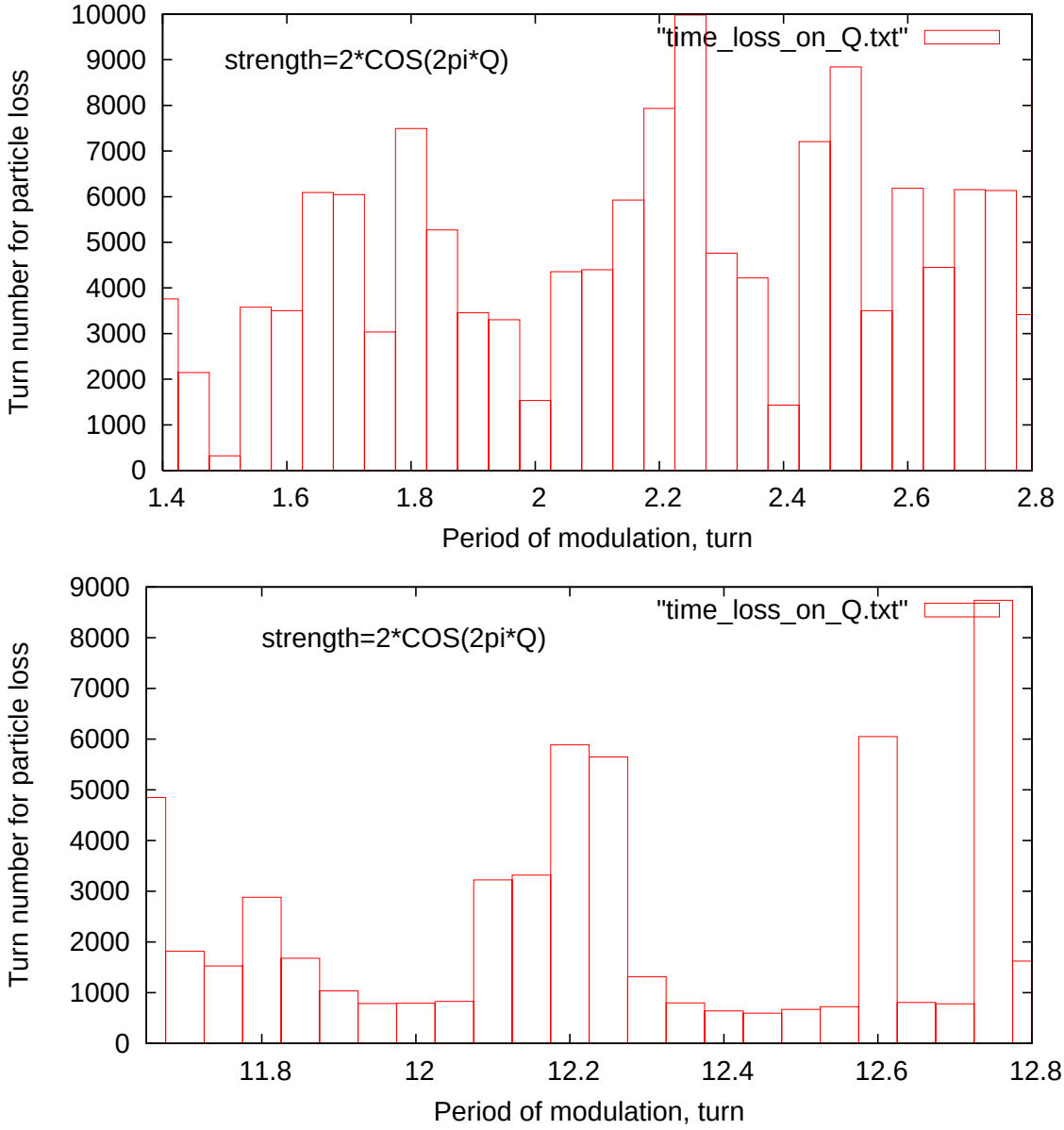

Figure 13: Turn number for particle loss as a function of period of E-lens strength modulation in the range of 1.4-2.8 turns (top) and 11.65-12.8 turns (bottom).

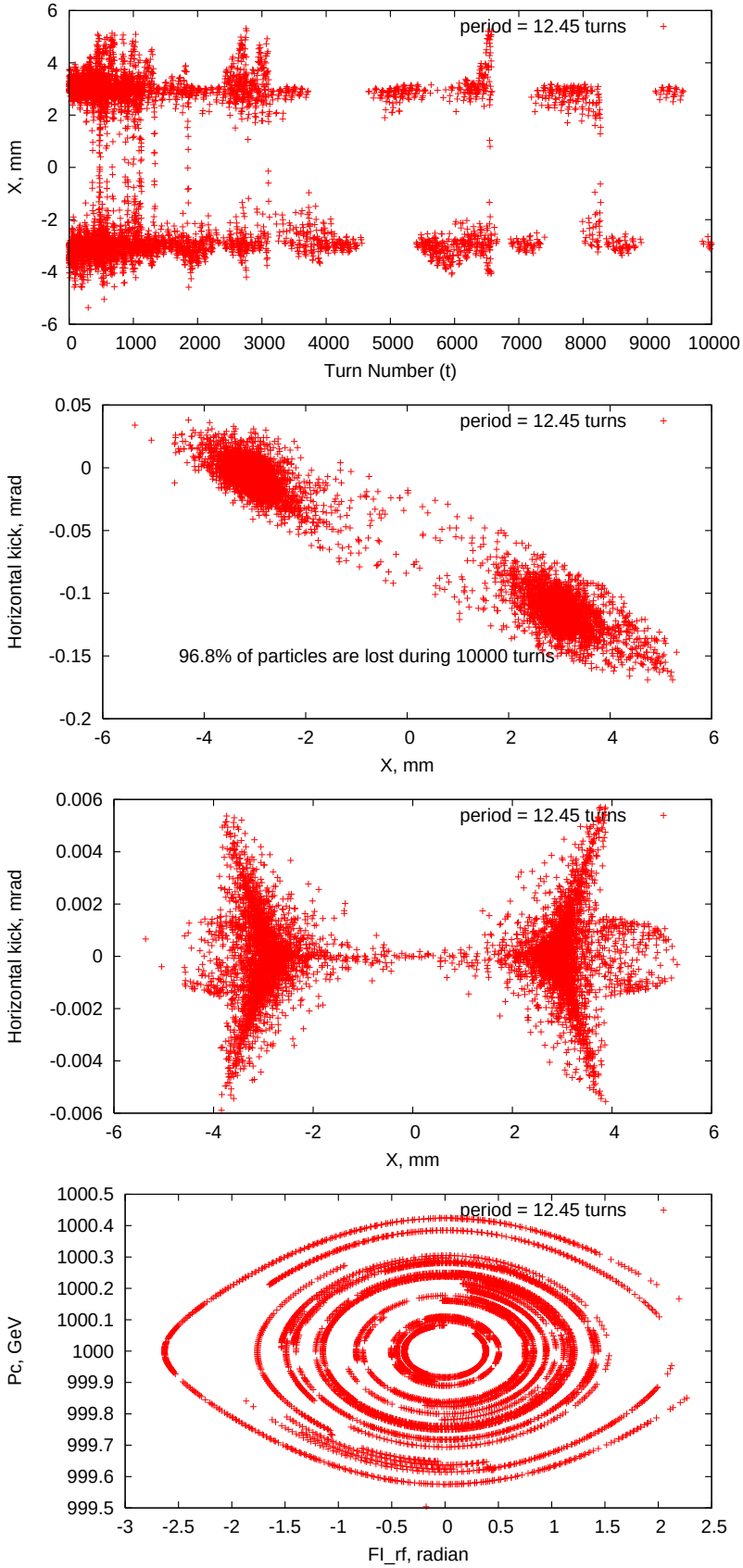

Figure 14: First 10 particle particle horizontal coordinate (top), betatron phase plane (second line), E-beam kick as a function of particle X coordinate (third line) for period of E-beam strength modulation of 12.45 turns. Amplitude of modulation is $0.003mrad \times COS(2\pi N/12.45)$. N is a turn number. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
21.974	0.110E-02	16	6.9905	34.30	34.30	3.3528	CB0Q2D
31.477	0.123E-02	30	5.9935	38.10	25.00	2.5718	B11VESE
2064.856	0.410E-03	2091	1.9979	25.00	38.10	2.5718	C49HESE
3109.904	0.350E+01	3187	32.9601	21.50	21.50	0.0050	colD49
3164.520	0.520E+00	3253	1474.5004	21.00	21.00	1.5000	colE03
3176.636	0.233E-03	3275	0.9266	34.30	34.30	2.1011	HQUAD2D
3197.194	0.253E-03	3295	2.9277	31.50	31.50	6.1214	BEND
3203.595	0.131E-03	3300	1.5201	31.50	31.50	6.1214	BEND
3226.073	0.799E-04	3324	0.9264	31.50	31.50	6.1214	BEND
3232.474	0.834E-04	3329	0.9665	31.50	31.50	6.1214	BEND
3255.817	0.837E-04	3354	0.9700	31.50	31.50	6.1214	BEND
3264.669	0.302E-02	3365	0.9821	34.30	34.30	0.1718	DQOUT
3338.646	0.857E-04	3439	0.9936	31.50	31.50	6.1214	BEND
4407.219	0.190E-01	4516	53.9279	23.70	21.00	1.5000	coF172
5204.709	0.347E-03	5337	0.9977	34.30	34.30	1.5198	DF49SP1
5267.588	0.446E+00	5398	1266.8470	20.00	20.00	1.5000	collA11
5285.498	0.293E-02	5420	0.7764	34.30	34.30	0.1397	DBENDEN
5291.759	0.332E-03	5423	3.8518	31.50	31.50	6.1214	BEND
5298.160	0.772E-04	5428	0.8949	31.50	31.50	6.1214	BEND
5314.071	0.830E-04	5447	0.9625	31.50	31.50	6.1214	BEND
5337.413	0.172E-03	5472	1.9954	31.50	31.50	6.1214	BEND
5343.814	0.862E-04	5477	0.9990	31.50	31.50	6.1214	BEND
5350.215	0.861E-04	5482	0.9984	31.50	31.50	6.1214	BEND
5356.616	0.861E-04	5487	0.9986	31.50	31.50	6.1214	BEND
5367.157	0.852E-04	5502	0.9873	31.50	31.50	6.1214	BEND
6189.431	0.861E-04	6329	0.9981	31.50	31.50	6.1214	BEND
6223.390	0.105E-01	6372	9.9863	30.00	30.00	0.5000	dumpA48
6241.148	0.861E-04	6400	0.9983	31.50	31.50	6.1214	BEND
6241.287	0.378E-02	6402	0.9990	34.30	34.30	0.1397	DBENDEN
6247.548	0.862E-04	6405	0.9988	31.50	31.50	6.1214	BEND
6249.538	0.188E-02	6410	0.9980	34.30	34.30	0.2805	DLB5
6254.285	0.820E-03	6421	3.9947	25.00	38.10	2.5718	A49HESE
6257.044	0.123E-02	6423	5.9911	38.10	25.00	2.5718	A49VESE
6259.803	0.205E-03	6425	0.9989	38.10	25.00	2.5718	A49VESE
6264.569	0.315E-03	6435	1.9975	34.30	34.30	3.3528	CB0Q2F
6265.446	0.181E-02	6436	2.9960	34.30	34.30	0.8763	DTRIPB

Table 5: Particle loss distribution along the accelerator at collimation for period of E-beam strength modulation of 12.45 turns. 96.8% of halo particles were collimated during 10,000 turns.

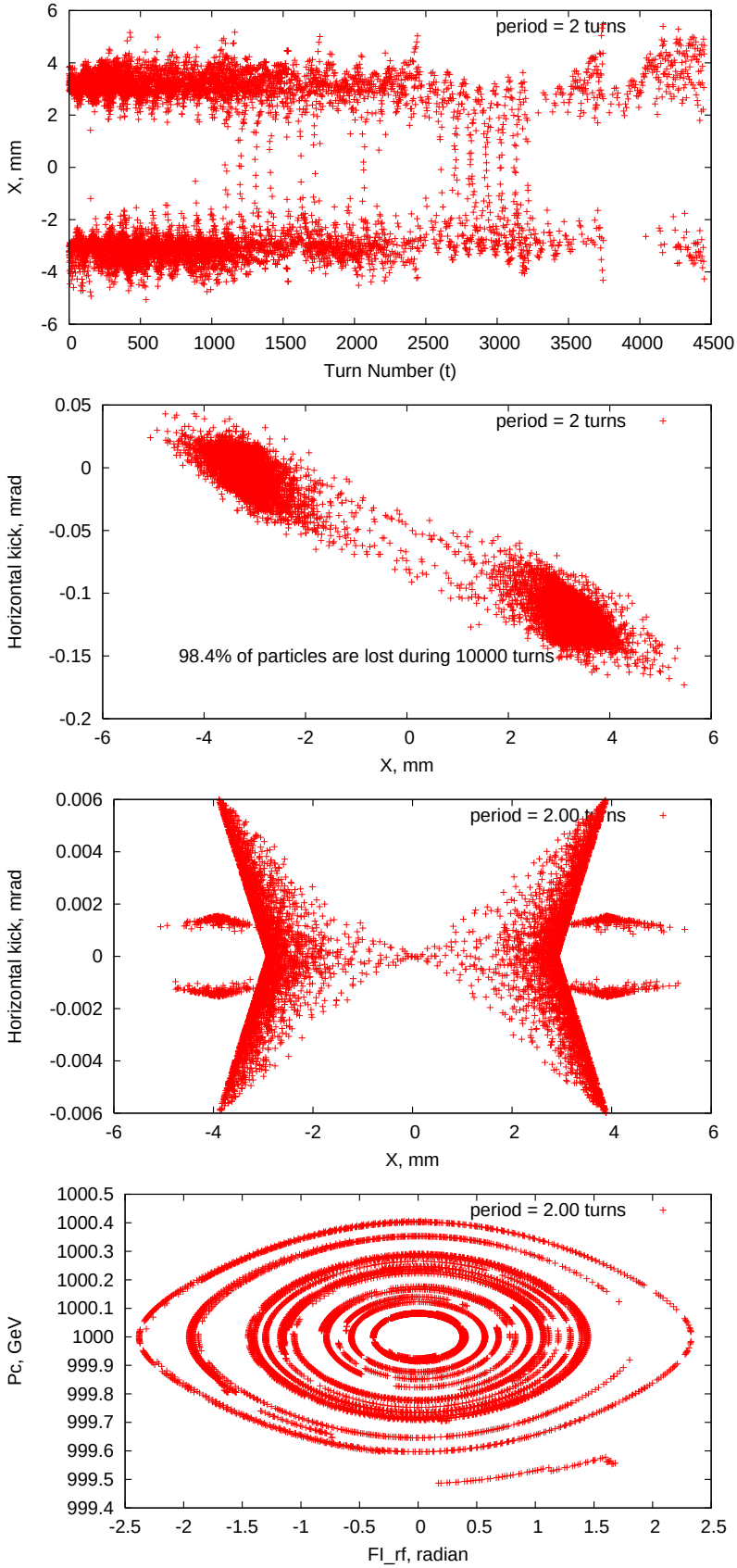

Figure 15: First 10 particle particle horizontal coordinate (top), betatron phase plane (second line), E-beam kick as a function of particle X coordinate (third line) for period of E-beam strength modulation of 2.00 turns. Amplitude of modulation is $0.003mrad \times COS(2\pi N/2.00)$. N is a turn number. Particle coordinates are printed only if particle is outside of internal radius of E-beam. Bottom is longitudinal phase plane.

S	LOSS	I	lost	APERTURE		LENGTH	NAME
(m)	(W/m)		(GeV/Po)	hor.	ver.	(m)	
21.974	0.157E-03	16	0.9991	34.30	34.30	3.3528	CB0Q2D
31.477	0.205E-03	30	0.9991	38.10	25.00	2.5718	B11VESE
3109.904	0.669E+01	3187	62.9327	21.50	21.50	0.0050	colD49
3164.520	0.945E+00	3253	2684.0228	21.00	21.00	1.5000	colE03
3197.194	0.691E-04	3295	0.8015	31.50	31.50	6.1214	BEND
3203.595	0.142E-03	3300	1.6486	31.50	31.50	6.1214	BEND
3204.195	0.229E-02	3304	0.8680	34.30	34.30	0.2000	DBPMOUT
3206.087	0.124E-02	3309	0.8967	34.30	34.30	0.3810	DHQUADC
3206.493	0.120E-02	3310	0.9247	34.30	34.30	0.4064	DPACKU2
3213.272	0.812E-04	3314	0.9418	31.50	31.50	6.1214	BEND
3219.672	0.172E-03	3319	1.9939	31.50	31.50	6.1214	BEND
3226.073	0.861E-04	3324	0.9987	31.50	31.50	6.1214	BEND
3232.474	0.862E-04	3329	0.9988	31.50	31.50	6.1214	BEND
3243.155	0.378E-02	3346	0.9993	34.30	34.30	0.1397	DBENDEN
3255.817	0.861E-04	3354	0.9980	31.50	31.50	6.1214	BEND
3410.935	0.861E-04	3506	0.9984	31.50	31.50	6.1214	BEND
4223.834	0.251E-03	4316	0.9984	34.30	34.30	2.1011	HQUAD2D
4407.219	0.204E-01	4516	57.9202	23.70	21.00	1.5000	coF172
5267.588	0.411E-01	5398	116.8870	20.00	20.00	1.5000	collA11
5379.958	0.856E-04	5512	0.9929	31.50	31.50	6.1214	BEND
6223.390	0.422E-02	6372	3.9946	30.00	30.00	0.5000	dumpA48
6241.287	0.378E-02	6402	0.9988	34.30	34.30	0.1397	DBENDEN
6250.044	0.104E-02	6411	0.9980	34.30	34.30	0.5063	DLB4
6257.044	0.205E-03	6423	0.9984	38.10	25.00	2.5718	A49VESE
6265.446	0.602E-03	6436	0.9985	34.30	34.30	0.8763	DTRIPB

Table 6: Particle loss distribution along the accelerator at collimation for period of E-beam strength modulation of 2.00 turns. 98.4% of halo particles were collimated during 10,000 turns.