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4.4 Lattice Design for Super Proton Proton Collider (SPPC)

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4.4.1 **Introduction**

With the discovery of the Higgs boson at the LHC, the world high-energy physics community is investigating the feasibility of a Higgs Factory as a complement to the LHC for studying the Higgs and pushing the high energy frontier. CERN physicists are busy planning the LHC upgrade program, including HL-LHC and HE-LHC. They also plan a more inspiring program called FCC, including FCC-ee and FCC-hh. Both the HE-LHC and the FCC-hh are proton-proton (pp) colliders aiming to explore the high energy frontier and expecting to find new physics [1, 2, 3]. Chinese accelerator physicists also plan to design an ambitious machine called CEPC-SPPC (Circular Electron Positron Collider-Super Proton Proton Collider). The CEPC-SPPC program contains two stages. The first stage is an electron-positron collider with center-of-mass energy 240 GeV to study the Higgs properties carefully. The second stage is a proton-proton collider at center-of-mass energy of more than 70 TeV [4]. The SPPC design is just starting, and first we developed a systematic method of how to make an appropriate parameter choice for a circular pp collider by using an analytical expression of beam-beam tune shift, starting from the required luminosity goal, beam energy, physical constraints at the interaction point (IP) and some technical limitations [5, 6]. Then we start the lattice design according to the parameter list and have the first version SPPC lattice.

4.4.2 **SPPC Parameter Choice**

The energy design goal of the SPPC is about 70-100 TeV, using the same tunnel as the CEPC, which is about 59 km in circumference [7, 8, 10]. A larger circumference for the SPPC, like 100 km, is also being considered. It is planned to use superconducting magnets of about 20 T [4]. We obtain a set of parameters for the 59.2 km SPPC. In this set of parameters, the full crossing angle θc keeps the separation of 12 RMS beam sizes for the parasitic crossings. The luminosity reduction factor due to the crossing angle is larger than 0.9 and the ratio of β^* and σ_z is about 15. We also give a set of parameters for the larger circumference SPPC, considering both 80 km and 100 km. Table 1 is the parameter list for the SPPC. We choose the dipole field as 20 T and get a center-of-mass energy of 70 TeV. If we want to explore the higher energy, we should make the circumference larger. To explore a center-of-mass energy of 100 TeV while keeping the dipole field at 20 T, the circumference should be 80 km at least. With this condition, there is hardly any space to upgrade, so a 100 km SPPC is much better because the dipole field is then only 15.52 T. If the dipole field is kept at 20 T in a 100 km SPPC, we can get a center-of-mass energy as high as 130 TeV [9, 11].

Table 1: SPPC Parameter List.

	SPPC(Pre-CDR	***SPPC-59.2Km***	***SPPC-100Km***	***SPPC-100Km***	***SPPC-80Km***
Main parameters and geometrical aspects					
Beam energy[E_0]/TeV	35.6	35.0	50.0	65.0	50.0
Circumference[C_0]/km	54.7	59.2	100.0	100.0	80.0
Dipole field[B]/T	20	19.70	15.52	19.83	19.74
Dipole curvature radius[ρ]/m	5928	5921.5	10924.4	10924.4	8441.6
Bunch filling factor[f_2]	0.8	0.8	0.8	0.8	0.8
Arc filling factor[f_1]	0.79	0.78	0.78	0.78	0.78
Total dipole length [L_{Dipole}]/m	37246	37206	68640	68640	53040
Arc length[L_{ARC}]/m	47146	47700	88000	88000	68000
Straight section length[Lss]/m	7554	11500	12000	12000	12000
Physics performance and beam parameters					
Peak luminosity per IP[L]/ $cm^{-2}s^{-1}$	1.1×10^{35}	1.20×10^{35}	1.52×10^{35}	1.02×10^{36}	1.52×10^{35}
Beta function at collision[β*]/m	0.75	0.85	0.99	0.22	1.06
Max beam-beam tune shift [ξy]/IP	0.006	0.0065	0.0068	0.0079	0.0073
Number of IPs contribut to ΔQ	2	2	2	2	2
Max total beam-beam tune shift	0.012	0.0130	0.0136	0.0158	0.0146
Circulating beam current[I_b]/A	1.0	1.024	1.024	1.024	1.024
Bunch separation[Δt]/ns	25	25	25	25	25

Number of bunches[n_b]	5835	6315	10667	10667	8533
Bunch population[N_p] (10^{11})	2.0	2.0	2.0	2.0	2.0
Normalized RMS transverse emittance[ε]/μm	4.10	3.72	3.62	3.10	3.35
RMS IP spot size[σ*]/μm	9.0	8.85	7.86	3.04	7.86
Beta at the 1st parasitic encounter[β_1]/m	19.5	18.70	16.36	68.13	15.31
RMS spot size at the 1st parasitic encounter[σ_1]/μm	45.9	43.20	33.31	55.20	31.03
RMS bunch length[σ_z]/mm	75.5	56.60	65.68	14.88	70.89
Full crossing angle[θc]/μrad	146	138.23	106.60	176.66	99.28
Reduction factor according to cross angle[*F*ca]	0.8514	0.9257	0.9247	0.9283	0.9241
Reduction factor according to hour glass effect[F_h]	0.9975	0.9989	0.9989	0.9989	0.9989
Energy loss per turn[U_0]/MeV	2.10	1.97	4.45	12.71	5.76
Critical photon energy[*E*c]/keV	2.73	2.60	4.11	9.02	5.32
SR power per ring[P_0]/MW	2.1	2.01	4.56	13.01	5.89
Transverse damping time [τ_x]/h	1.71	1.946	2.08	0.946	1.28
Longitudinal damping time [τ_ε]/h	0.85	0.973	1.04	0.473	0.64

4.4.3 SPPC Lattice Consideration

4.4.3.1 *ARC length consideration and limitation*

According to the SPPC physicists, we want to find some new physics on this big ambitious machine. The center-of-mass energy should be 70 TeV at least and between 70 TeV and 100 TeV will be much better. We will use high field dipole in ARC and its strength will be 20T. Now we estimate the circumference length. If we choose the lowest CMS energy 70 TeV, then we have the smallest B*ρ (116635.29Tm).* We use the highest strength of dipole 20T, then we have the smallest dipole radius *ρ(5831.76m)* and the smallest total dipole length (36.6 km). If the arc filling factor in ARC is 0.8, an usual choice and much reasonable number, then we can get the total ARC length (L_{ARC}

=47.8 km). There are 8 long straight sections and 2 of them are about 3 km long at IP1 and IP3 for ee integration region. And now the other 6 long straight sections are about 1km in the same length. So the circumference will be about 59.5 km.

4.4.3.2 *Layout consideration*

According to the Pre-CDR and CEPC partial double ring layout [10, 11], in the future, SPPC is in the same tunnel with CEPC and may be running at the same time. So the layout of SPPC should consider the CEPC layout. Fig. 1 shows the layout of SPPC according the layout of CEPC partial double ring scheme.

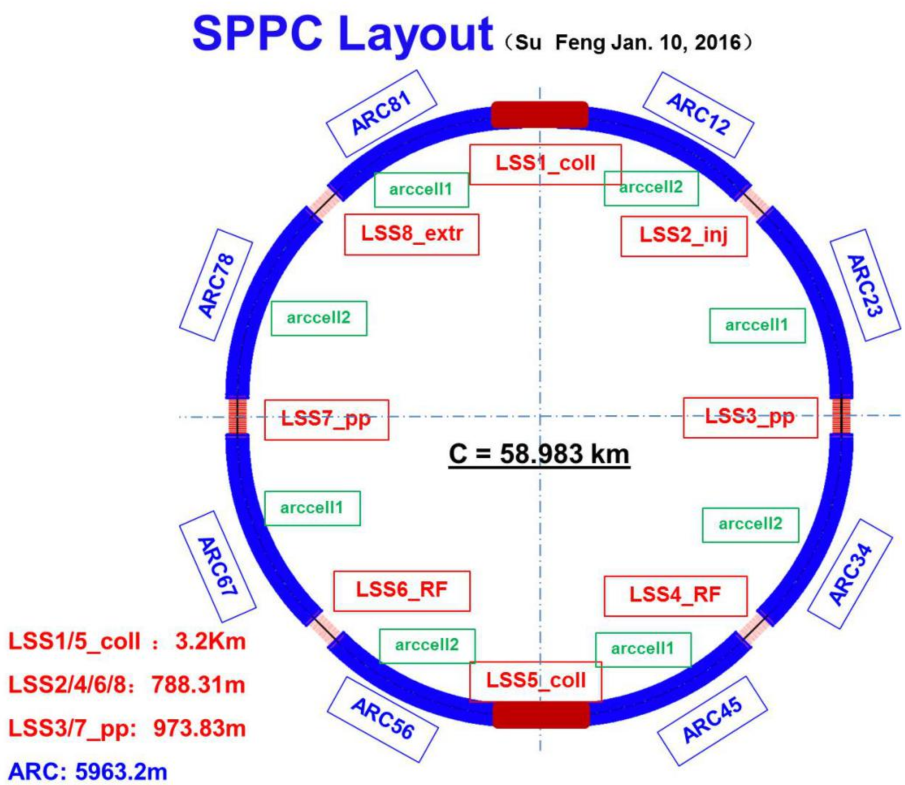


Figure 1: SPPC Lattice Layout.

4.4.4 **SPPC Lattice Design**

4.4.4.1 *ARC and FODO cell*

In this part, we introduced the preliminary lattice design of SPPC. There are 8 arcs and 8 long straight sections. We use FODO in the ARC, and Fig. 2 shows the parameters of FODO cell in ARC. Each cell has 8 dipoles whose length is 14.8 m and strength is 20 T. The total cell length is 144.4 m, maximum beta function is 244.8 m, minimum beta function is 42.6 m and phase advance is 90 degree in both horizontal and vertical. The quadrupole gradient and dipole parameter is reasonable according to the

Pre-CDR choice. And the aperture of quadrupole is also reasonable for both injection and collision energy. Fig. 3 and Fig. 4 is the optics of FODO cell and ARC.

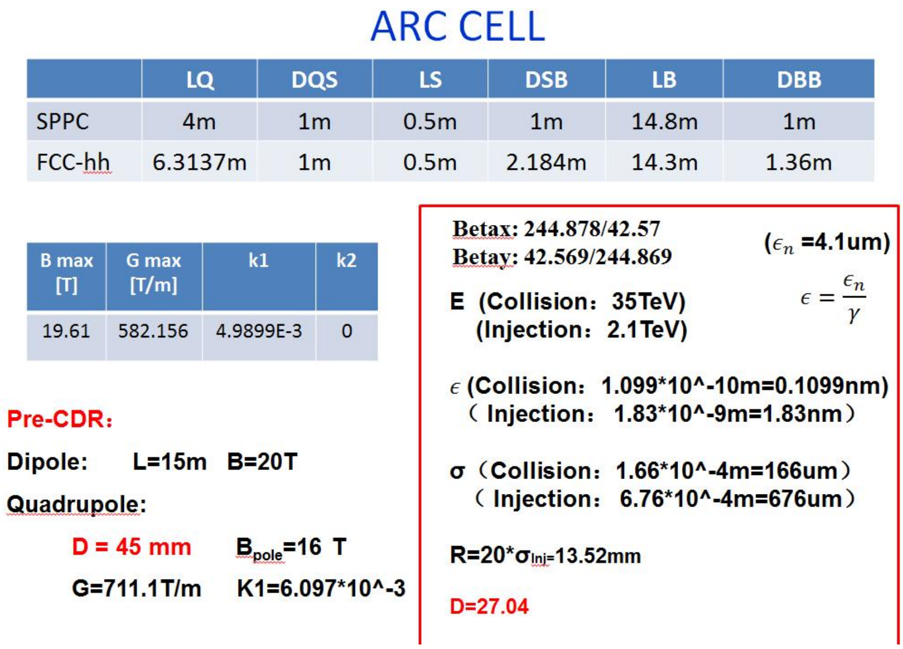


Figure 2: SPPC FODO cell parameter choice.

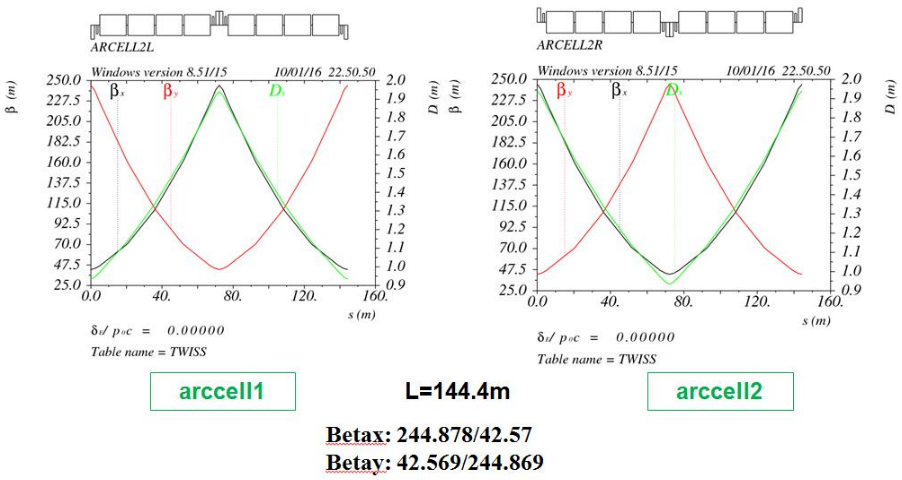


Figure 3: SPPC FODO cell optics.

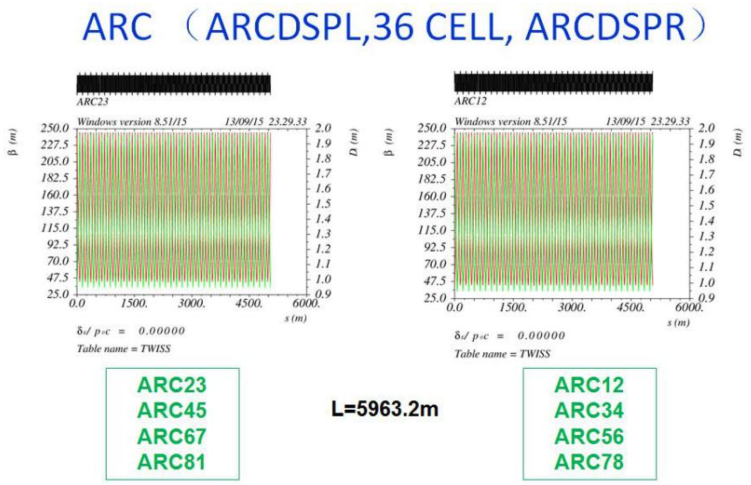
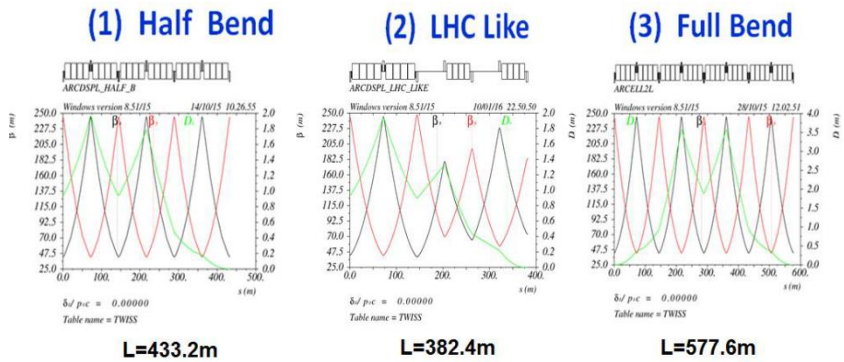


Figure 4: SPPC ARC optics.

4.4.4.2 *Dispersion Suppressor Section*

For 90 degree phase advance FODO cell, the dispersion suppressor section has three schemes, called full-bend scheme, half-bend scheme and missing-dipole scheme. Fig. 5 shows these three schemes for SPPC. And in our design we choose the missing-dipole scheme as the space can be used for collimation in the future.



	BDSP1L	BDSP2L	BDSP1R	BDSP2R	B0	
(1)	9.805	9.805	9.805	9.805	19.61	(T)
(2)	18.93	18.93	18.93	18.93	19.61	(T)
(3)	19.61	19.61	19.61	19.61	19.61	(T)

Figure 5: Dispersion suppressor section for SPPC.

4.4.4.3 *Long Straight Section and Interaction Region*

There are 8 long straight sections in SPPC lattice which are named as LSS1_coll, LSS2_inj, LSS3_pp, LSS4_RF, LSS5_coll, LSS6_RF, LSS7_pp and LSS8_extr. Long straight section 3 and 7 are for low β pp collision, long straight section 1 and 5 are for collimation using the long space as 3.2 km, long straight section 4 and 6 are for RF system and long straight section 2 and 8 are for injection and extraction. Fig. 6 7 8 9 show the optics of these long straight sections. Fig. 10 shows the quadrupole strength of

LSS3_pp and LSS7_pp, and the gradient and aperture are reasonable according to the Pre-CDR parameter choice for quadrupoles.

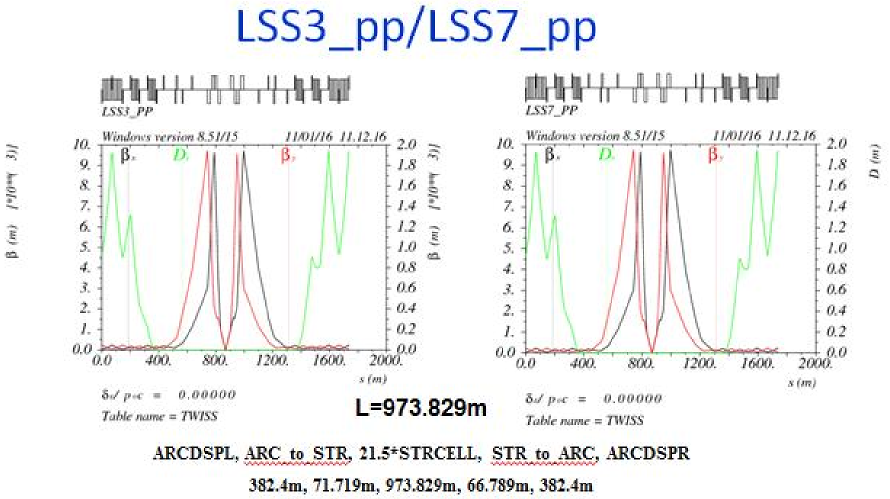


Figure 6: Long straight section for low β pp collision.

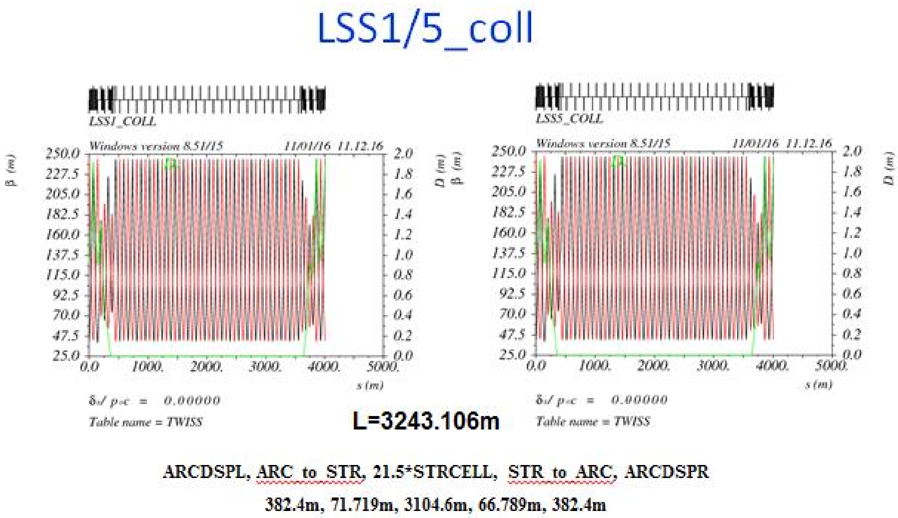


Figure 7: Long straight section for collimation.

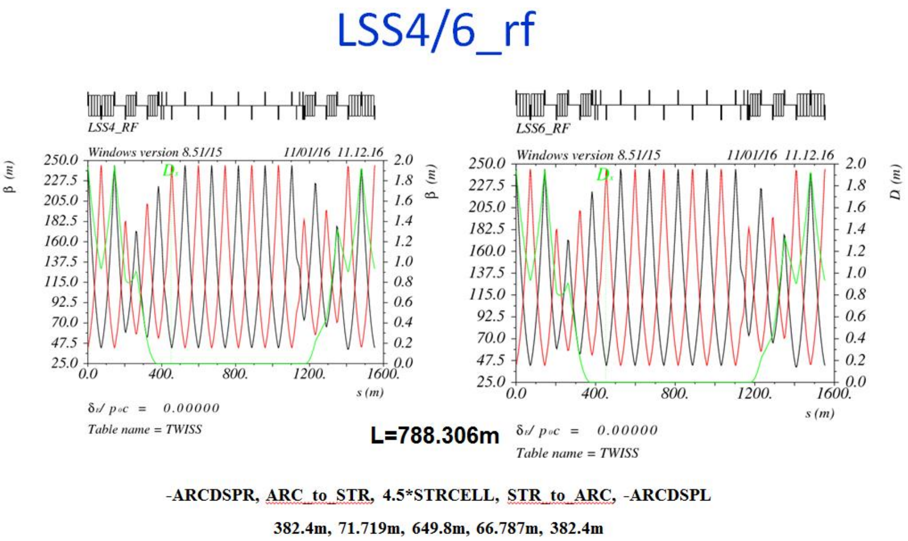


Figure 8: Long straight section for RF system.

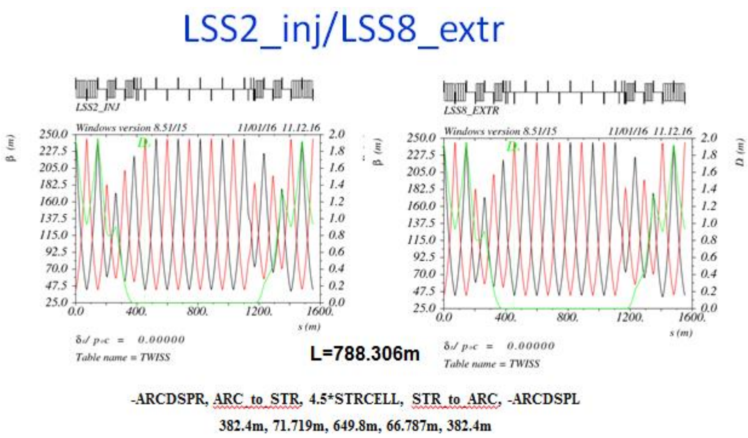


Figure 9: Long straight section for injection and extraction.

R	K1(m^-2)	G（T/M）	L(M)	βmax	L	K1(m^-2)	G（T/M）	L(M)	βmax
K1.QT.1R	4.9751e-03	580.428	6	3543.69	K1.QT.1L	-4.9751e-03	-580.428	6	3543.69
K1.QT.A2R	-5.2595e-03	-613.668	9	9601.686	K1.QT.A2L	5.2595e-03	613.668	9	9601.686
K1.QT.B2R	-5.2595e-03	-613.668	9	9601.686	K1.QT.B2L	5.2595e-03	613.668	9	9601.686
K1.QT.3R	5.3434e-03	623.369	8	9731.53	K1.QT.3L	-5.3434e-03	-623.369	8	9731.53
K1.QM.4R	-2.2804E-04	-266.04	4	3798.29	K1.QM.4L	2.2804E-04	266.04	4	3798.29
K1.QM.5R	8.8592E-04	103.36	4	1506.53	K1.QM.5L	-8.8592E-04	-103.36	4	1506.53
K1.QM.6R	-1.2144E-03	-141.68	4	587.87	K1.QM.6L	1.2144E-03	141.68	4	587.87
K1.QM.7R	1.0640E-04	124.133	4	531.25	K1.QM.7L	-1.0640E-04	-124.133	4	531.25
K1.QM.8R	-4.2431E-03	-495.028	4	162.20	K1.QM.8L	4.2431E-03	495.028	4	162.20

Figure 10: Quadrupole gradient and aperture in LSS3_pp and LSS7_pp.

4.4.5 Dynamic Aperture Study and Beam Dynamics

Dynamic aperture study is a very important and interesting issue in pp colliders. The Dynamic aperture is divided into 2 kinds. One is called Real-World-Dynamic-

Aperture (RW-DA) which is defined as the largest amplitude at which particles remain in the accelerator over a time range of interest. The other one is called Potential-Dynamic-Aperture (PO-DA) which is defined as the onset of global chaos, also means the largest amplitude with mainly regular motion. Insignificant chaotic layers within the regular regime will be ignored. However considerable wide "chaotic spikes" have to be taken into account. It turns out that the PO-DA is typically too small as RW-DA estimate. The chaotic motion is measured by the evolution of initially close-by particles. And the Lyapunov exponent is a sensitive signal for DA tracking.

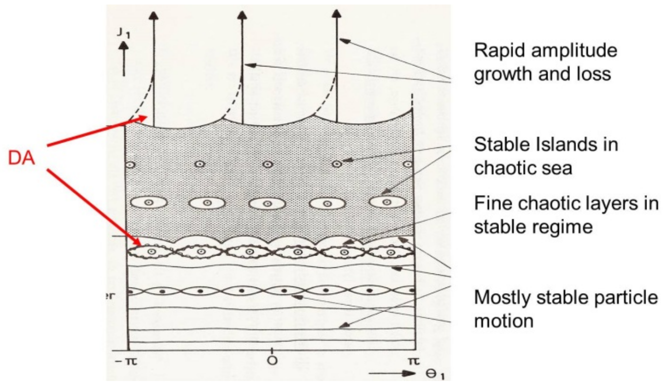


Figure 11: Dynamic Aperture Scheme

4.4.5.1 *Dynamic Aperture without Interaction Region*

At first, we studied the dynamic aperture of SPPC main ring without interaction region. There are 8 arcs in the main ring and 8 long straight sections. Now we use simple FODO in the long straight section, latter we should optimize the long straight section design for difference use like RF system, injection, extraction and collimation.

Following is the dynamic aperture from Sixtrack. Figure 12 is a 4-Dimension phase space for the regular and the chaotic motion. The solid tie shape shows the regular particles motion which has the largest amplitude, if the amplitude becomes a little larger, the motion will become chaotic, and the diffusion points around the solid tie show the chaotic motion. This largest amplitude is the dynamic aperture we want to study. Figure 13 shows the evolution of the distance of phase space for regular (left) and chaotic (right) motion. Figure 14 and Figure 15 show the horizontal and vertical phase space projections for the regular (left) and the chaotic (right) cases. Figure 16 show the physical phase space projections for the regular (left) and the chaotic (right) cases. Figure 17 and Figure 18 show the horizontal and vertical tune FFT-analysis for the regular (left) and the chaotic (right) cases. We can get from the figures that the dynamic aperture is about 22.58 mm (346 σ_x) in horizontal and 49.16 mm (315 σ_y) in vertical.

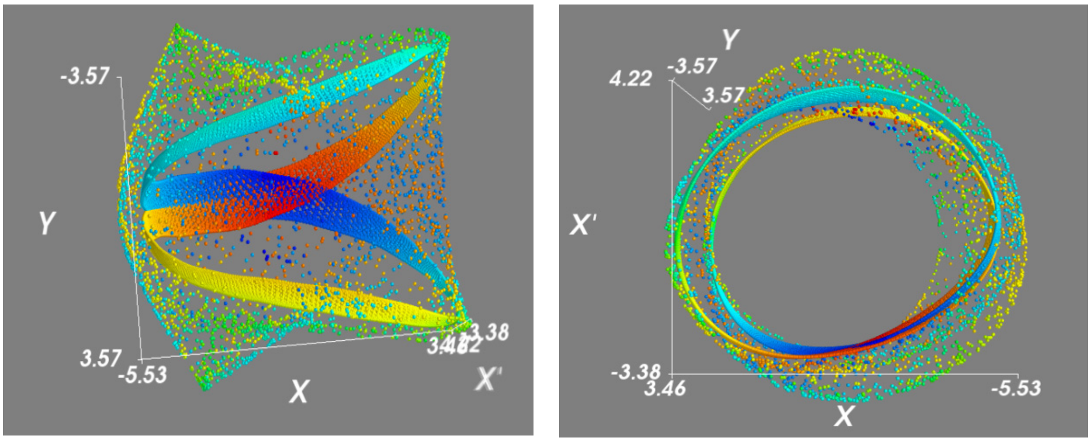


Figure 12: 4-Dimension phase space for regular and chaotic motion (cm).

(The solid tie shape shows the regular particles motion which has the largest amplitude, if the amplitude becomes a little larger, the motion will become chaotic, the diffusion points around the solid tie show the chaotic motion. This largest amplitude is the dynamic aperture we want to study.)

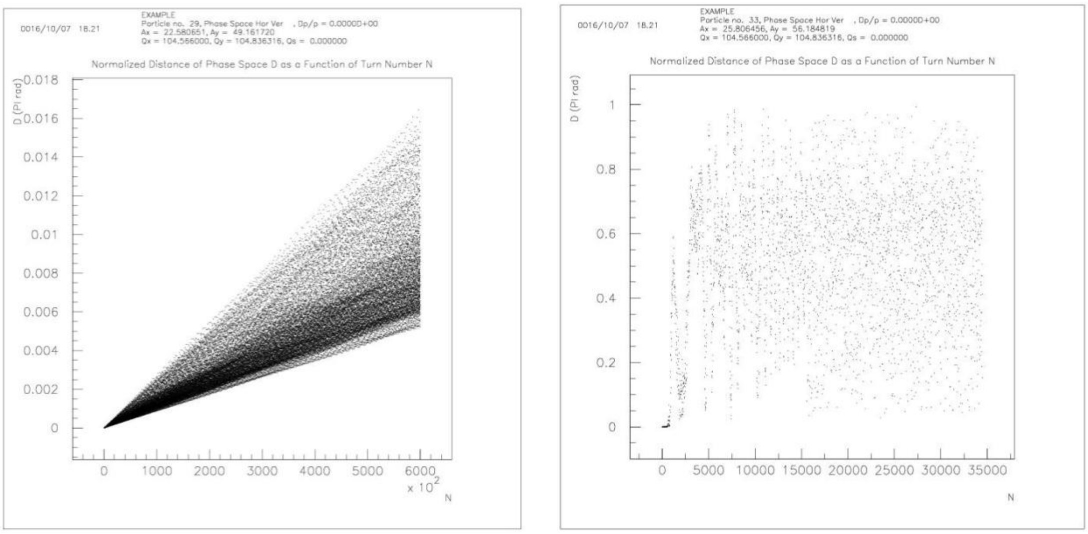


Figure 13: Evolution of the distance of phase space for regular (left) and chaotic (right) motion.

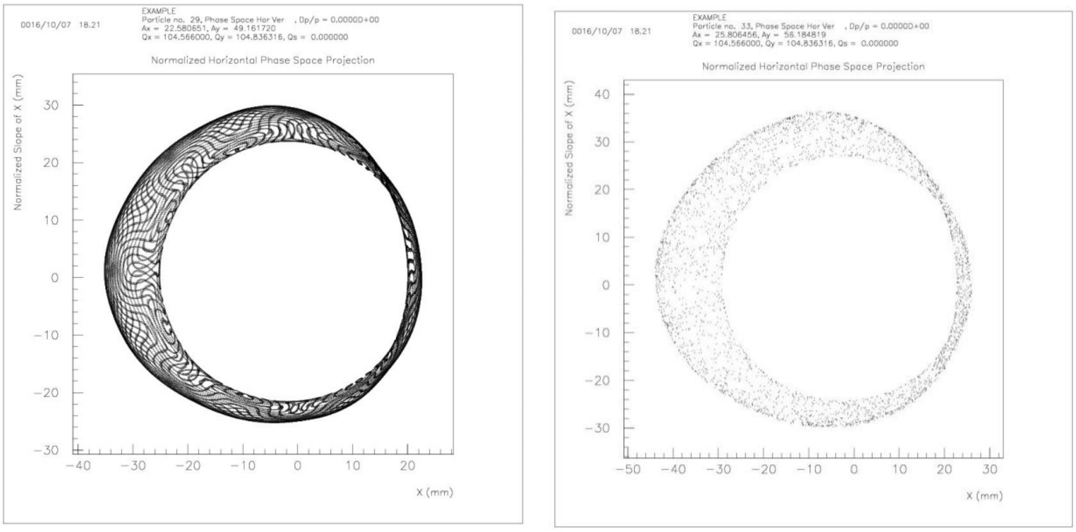


Figure 14: Horizontal phase space projections for regular (left) and chaotic (right) cases.

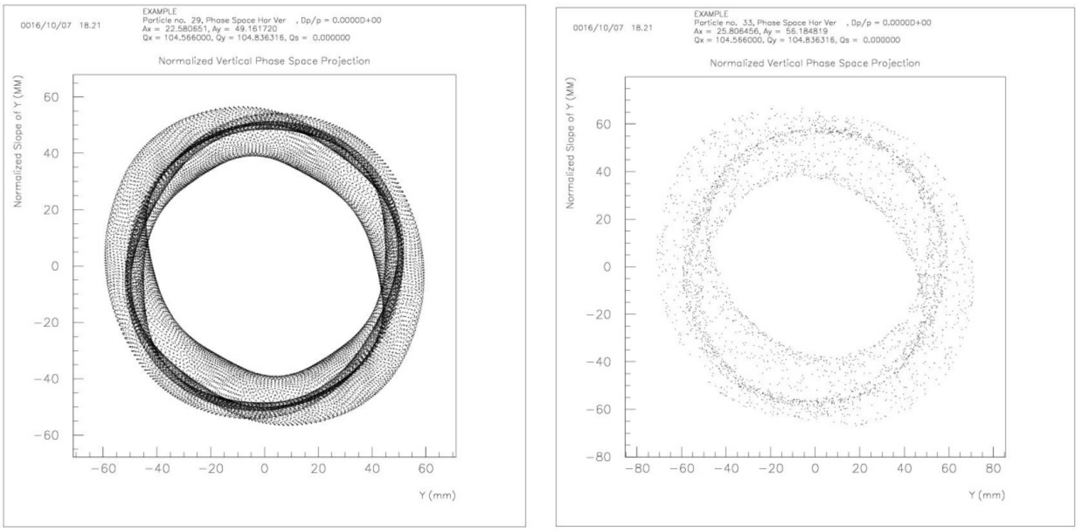


Figure 15: Vertical phase space projections for regular (left) and chaotic (right) cases.

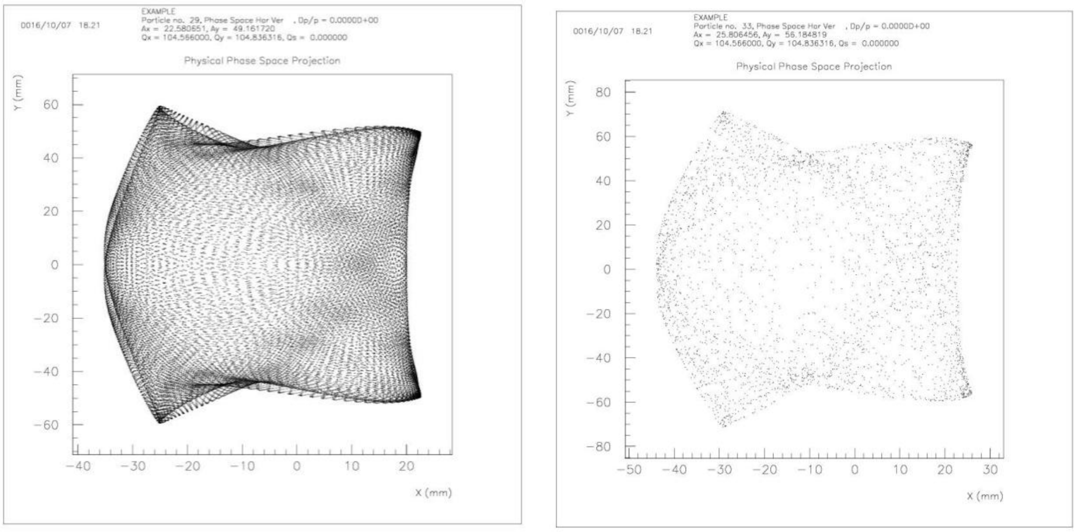


Figure 16: Physical phase space projections for regular (left) and chaotic (right) cases.

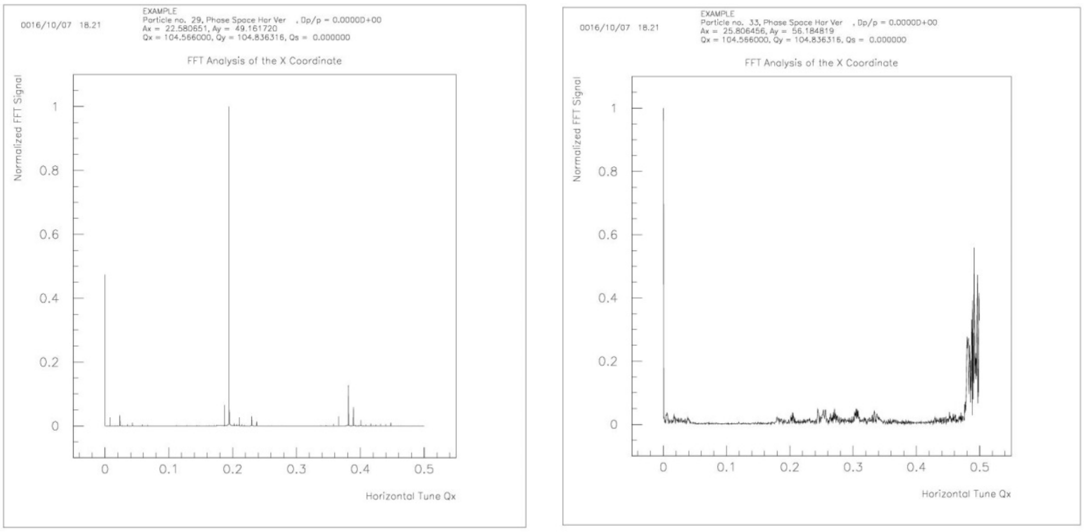


Figure 17: Horizontal FFT-analysis for the regular (left) and the chaotic (right) cases.

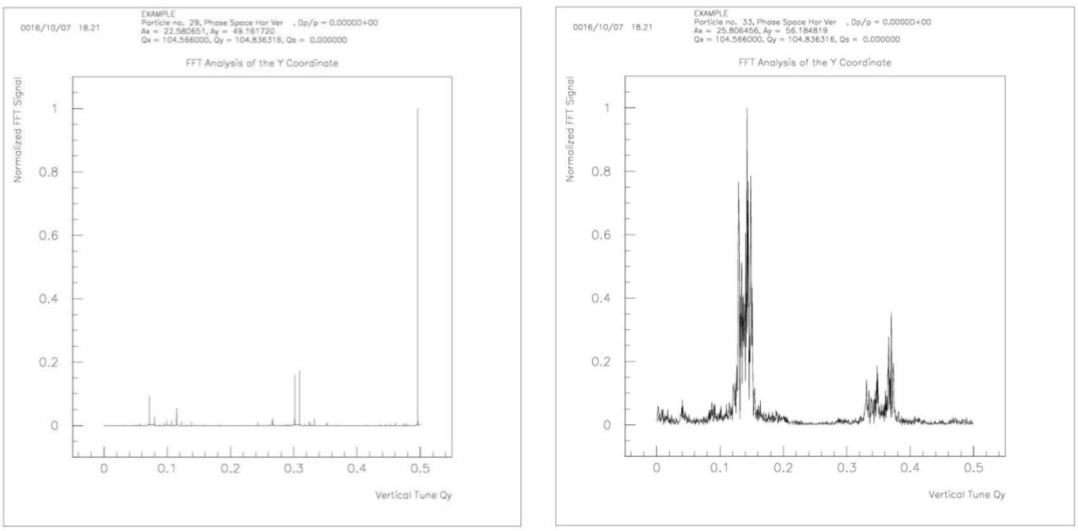


Figure 18: Vertical FFT-analysis for the regular (left) and the chaotic (right) cases.

4.4.5.2 *Dynamic Aperture with Interaction Region*

Following is the dynamic aperture with low beta pp interaction region. The beta function at IP is 0.75m. The maximum beta function in this region is about 9.6 km. The dynamic aperture becomes smaller, 8.22 mm (126 σx) in horizontal and 19.73 mm (126 σy) in vertical (we keep the same observation point for comparison with the DA without low beta pp IR). At the low beta pp IP, the dynamic aperture is only 1.089mm (126 σ) in both horizontal and vertical because the beam size is very small (8.647um).

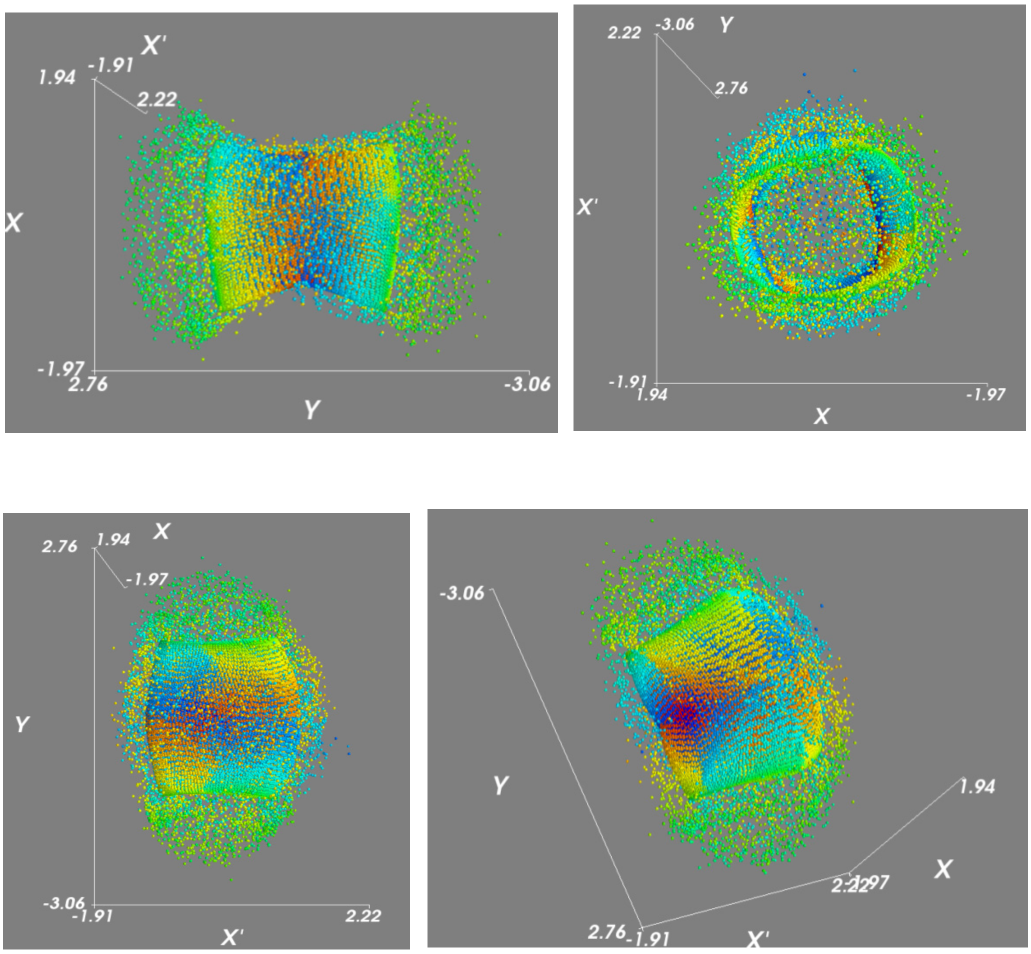


Figure 19: 4-Dimension phase space for regular and chaotic motion (cm).

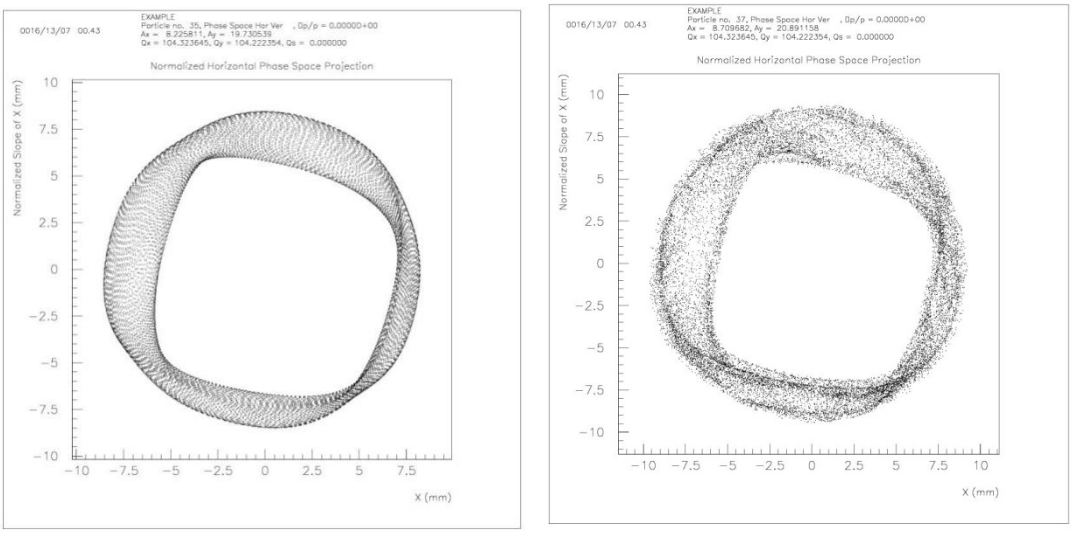


Figure 20: Horizontal phase space projections for regular (left) and chaotic (right) cases.

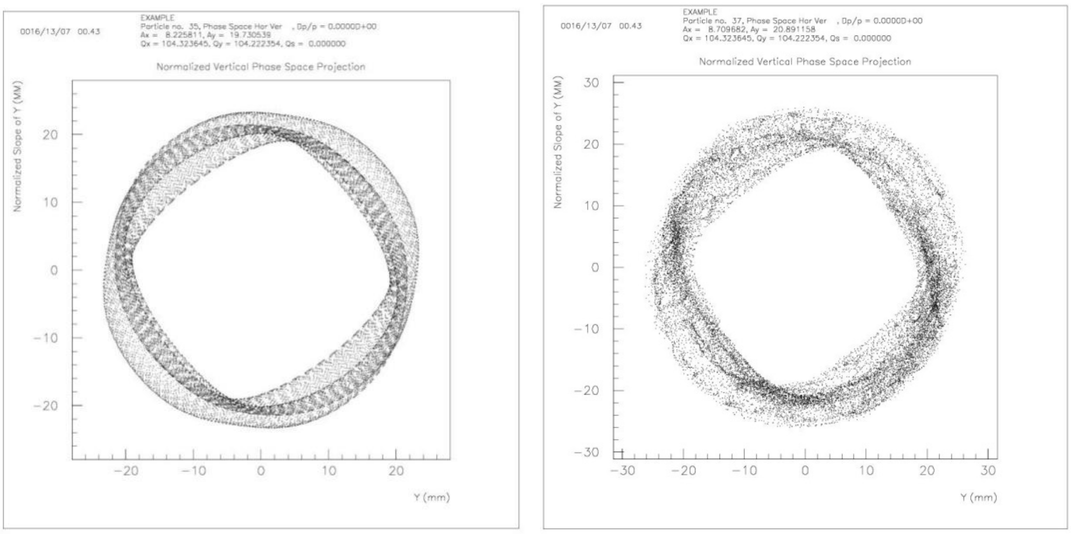


Figure 21: Vertical phase space projections for regular (left) and chaotic (right) cases.

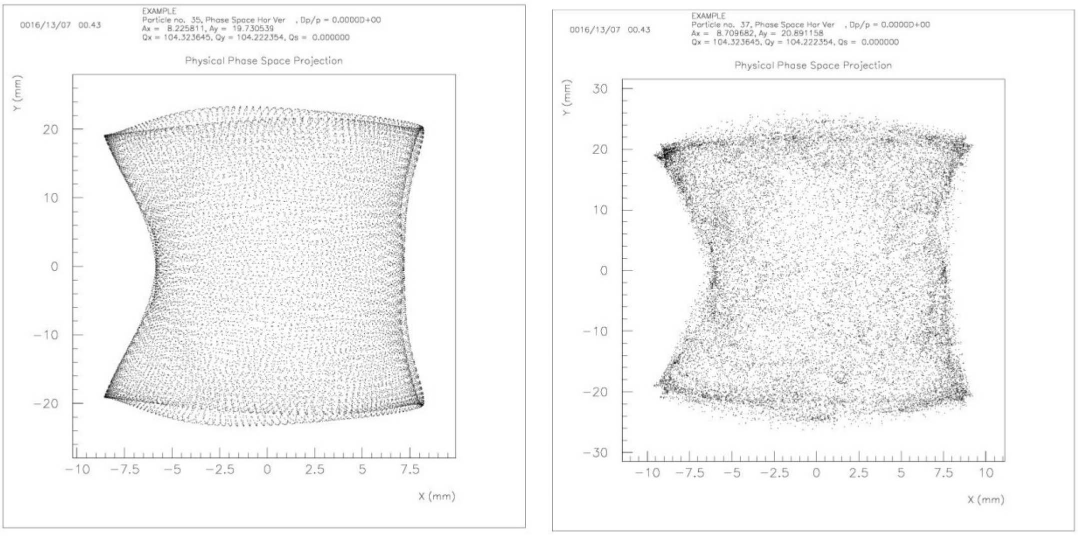


Figure 22: Physical phase space projections for regular (left) and chaotic (right) cases.

4.4.6 **Summary**

In this paper, we showed a set of parameters for SPPC with different circumferences like 59km, 80 km or 100 km and different energies like 70TeV or 100TeV. We also showed the first version of SPPC lattice including ARC, dispersion suppressor section and long straight sections. We also showed the first dynamic aperture and beam dynamic studies of SPPC main ring with and without low beta pp interaction region although it needs lots of work to do and to be optimized.

4.4.7 **References**

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