Weak-strong simulation of beam-beam effects in SPPC

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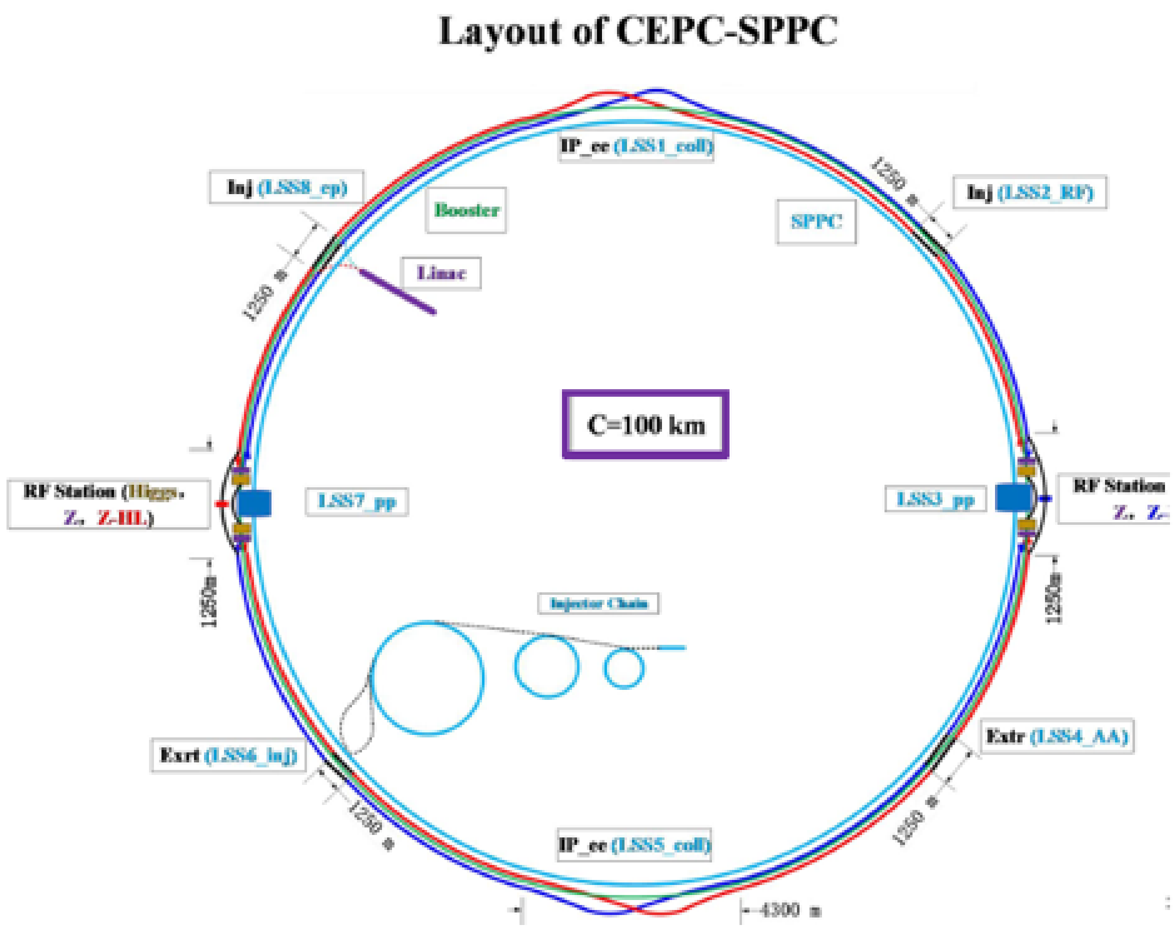
Physics Goals of CEPC-SPPC

Electron-positron collider (45.5, 80, 120 GeV)

- Higgs Factory
  - Precision study of Higgs (m_H, J^{PC}, couplings)
  - Looking for hints of new physics
- Z & W factory
  - Precision test of standard model
  - Rare decays

Proton-proton collider(75 TeV)

- Directly search for new physics beyond SM
- Precision test of SM



From CEPC to SPPC

- CEPC first to be built, with potential to add SPPC later
- SPPC is built in the same CEPC tunnel to explore new physics beyond Standard Model
- Center-of-Mass energy larger than 70 TeV with possible energy upgrade
- Keep the e-/e+ rings when adding the SPPC
- Collisions possible: pp, e-/e+, ep, pA, eA, AA
- Build a new injector chain for SPPC (proton and ions)
- Independent physics programs for the accelerators of the injector chain

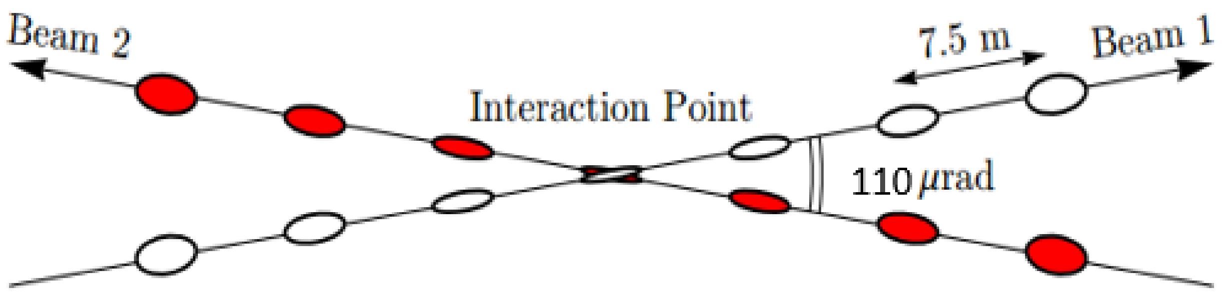
Contents

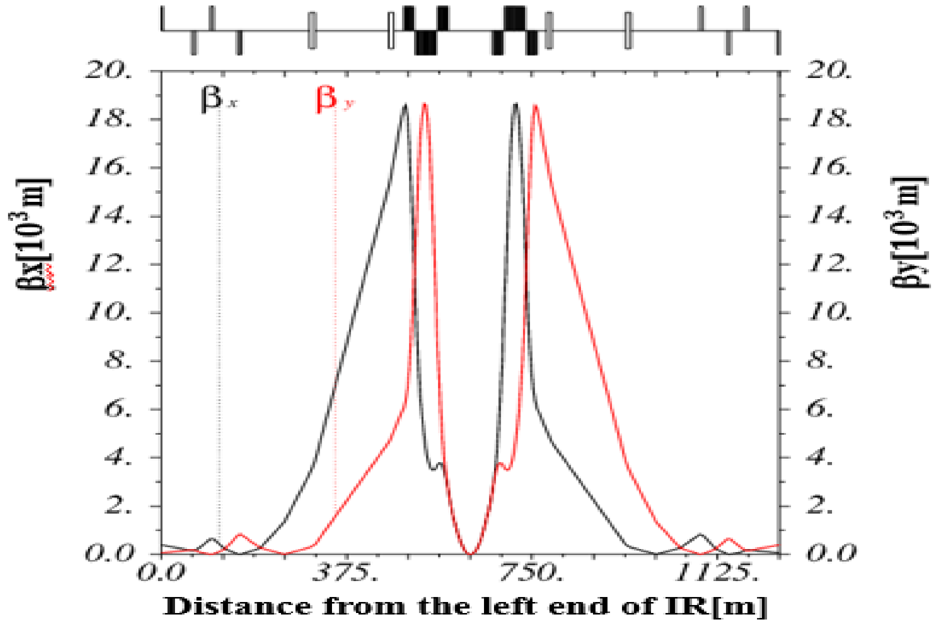
- SPPC nominal parameters
- SPPC optics features in interaction region(IR)
- SPPC tune footprints, Frequency map analysis(FMA) plots and dynamic aperture(DA)
- Tune scan studies
- Different crossing angle and β^*
- Long-range interaction compensation
- Conclusion

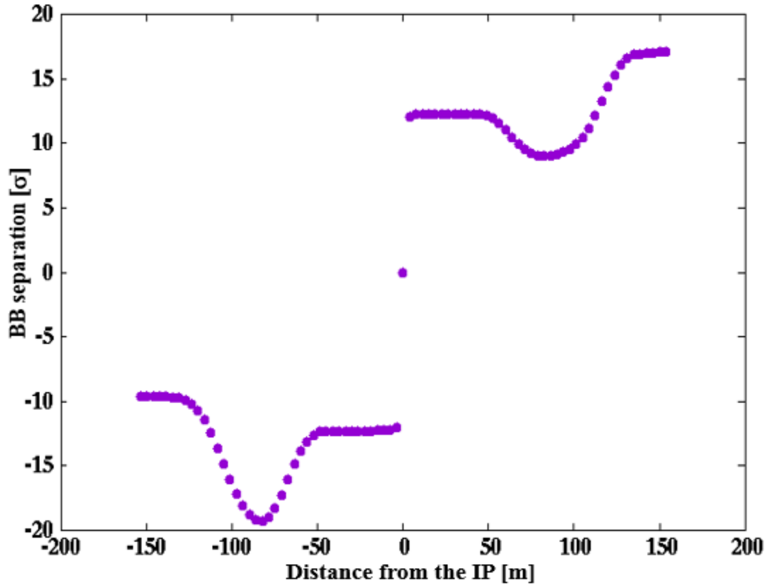
- SPPC parameters

SPPC relative parameter	**Value**		**Unit**
	CDR	Ultimate	
Circumference	100	100	km
Beam energy	37.5	62.5-75	TeV
Number of IPs	2	2	
Revolution frequency	3	3	kHz
Physics performance and beam parameters			
Peak luminosity per IP	1.01×10^{35}	-	$cm^{-2}s^{-1}$
Beta function at collision	0.75	-	m
Circulating beam current	0.7	-	A
Nominal beam-beam tune shift limit per IP	0.0075	-	
Bunch separation	25	-	ns
Number of bunches	10080	-	
Bunch population	1.5×10^{11}	-	
Normalized rms transverse emittance	2.4	-	μm
Full crossing angle	$12\ \sigma'$	-	

• SPPC optics features in IR







- ➢ there are 82 long-range interactions(LRIs) and 1 head-on interaction(HDI) in each IR, the total is 164 LRIs and 2 HDIs.
- ➢ the optics is antisymmetric in interaction region, $\beta*$ is 0.75m, the largest β is 18660m
- ➢ The minimum separation is 9~10σ, which occurs at 20 parasitic interactions in each IR.

• SPPC tune footprints, FMA plots and dynamic aperture

The weak-strong simulations reported here are done using the code BBSIM[1]

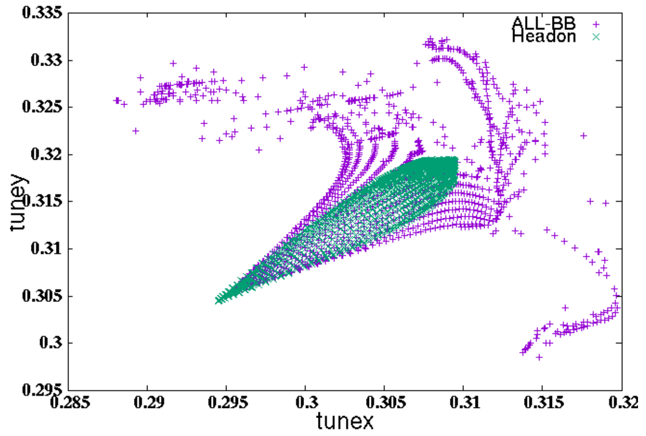


Figure1: Green points is the tune footprint of head-on interactions, violet points is the tune footprint with all of interactions.

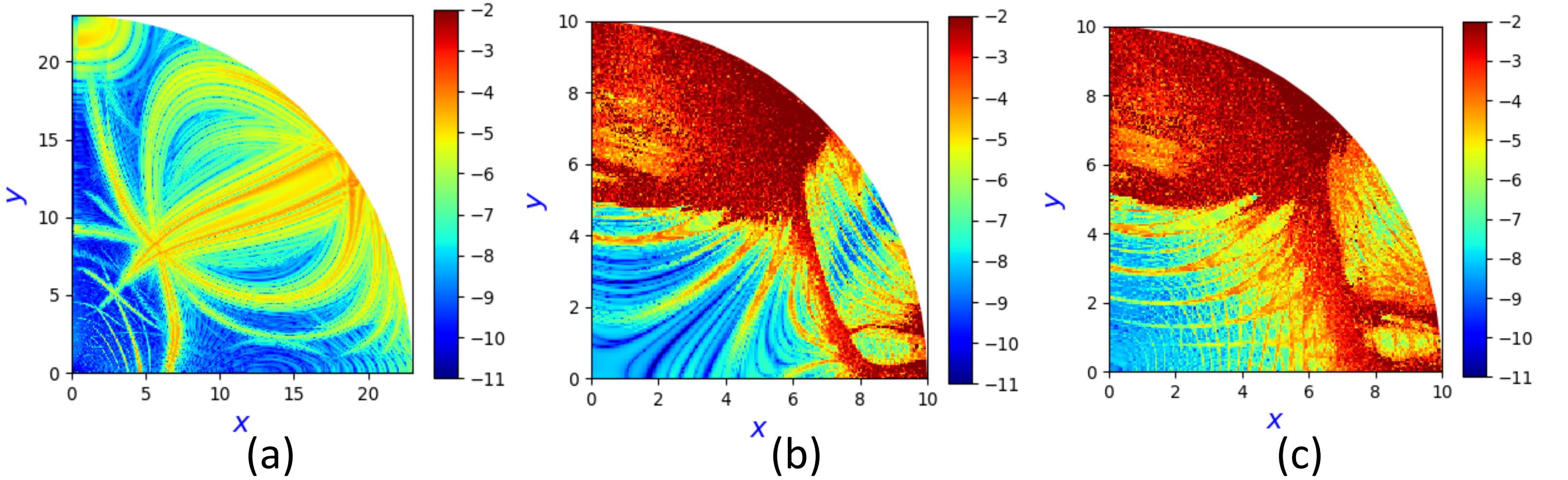


Figure 2: FMA plots for 3 cases. (a): head-on and sextupole kick. (b): long-range and sextupole kick. (c): head-on, long-range and sextupole kick.

- In the nominal lattice design, the tune is (120.31, 117.32), the fractional parts is same as the LHC design.
- the nonlinearities are from the chromaticity correcting sextupoles and beam beam interactions.
- FMA plots show the tune variation become obviously worse when there are LRIs.

[1] H.J. Kim and T Sen, "Beam-beam simulation code BBSIM for particle accelerators", in *Nucl.Instrum.Meth. A642*, June, 2011

- SPPC tune footprints, FMA plots and dynamic aperture

Dynamic aperture (DA) calculations are done in six dimensional phase space with particles tracked for a million turns

	DA-averaged	DA-smallest	Physical aperture
Sextupole kick	23 σ	23 σ	23 σ
Sextupole + headon	23 σ	23 σ	23 σ
Sextupole + longrange	6.20 σ	4.50 σ	23 σ
Sextupole + headon + longrange	5.52 σ	4.75 σ	23 σ

- Tracking with only the sextupoles and the head-on interactions show that the DA is the same as the physical aperture of 23 σ.
- Adding the long-range interactions reduces the DA to 5.5 σ, which is unacceptably low. Comparing the smallest DA among 4 cases above, it also proves that LRIs will cause a worse DA.
- Long-range interactions are the main factor limiting particle stability and the DA in the SPPC baseline design is only 5.5 σ

• Tune scan studies

We scanned the tunes in the range (0.10 ≤. $\upsilon x \le 0.46$), ($\upsilon y = \upsilon x \pm 0.01$ or 0.02)

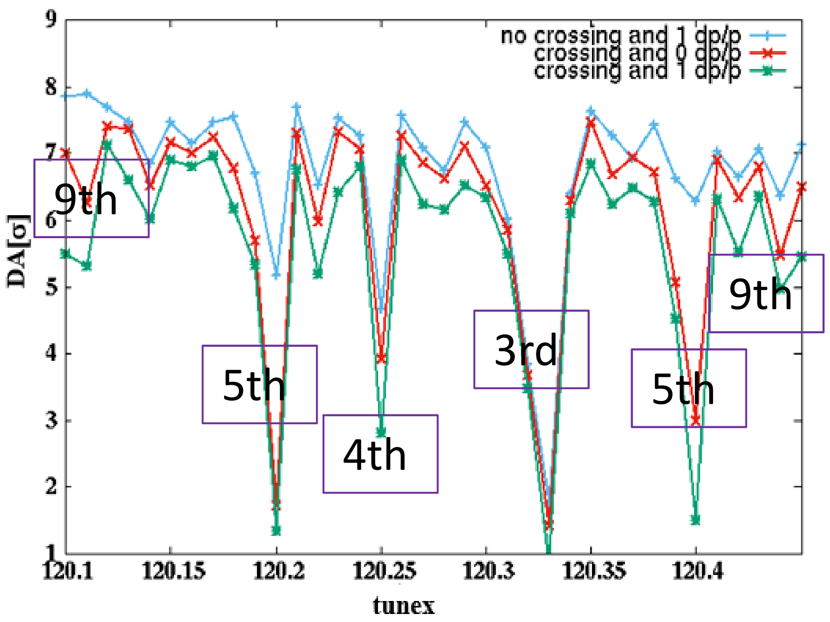


Figure 3: Average DA with different υx. $\upsilon y = \upsilon x \pm 0.01$; red; with crossing angle and no $\Delta p/p$ (momentum deviation); green: with crossing angle and $\Delta p/p = \sigma p$ (rms momentum spread); blue: without crossing angle and $\Delta p/p = \sigma p$.

rms momentum spread 7.074480e-05

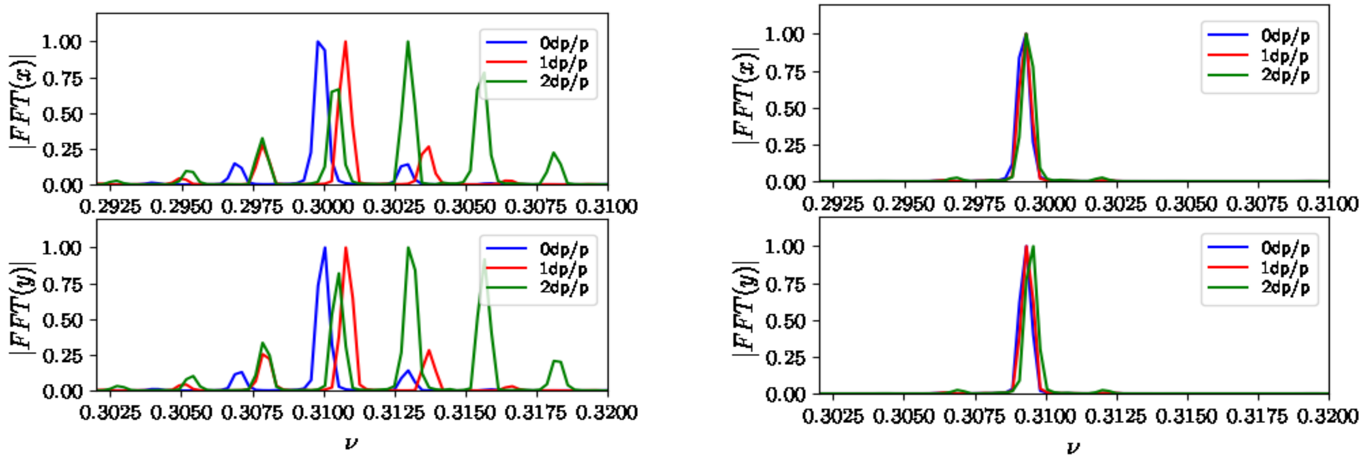
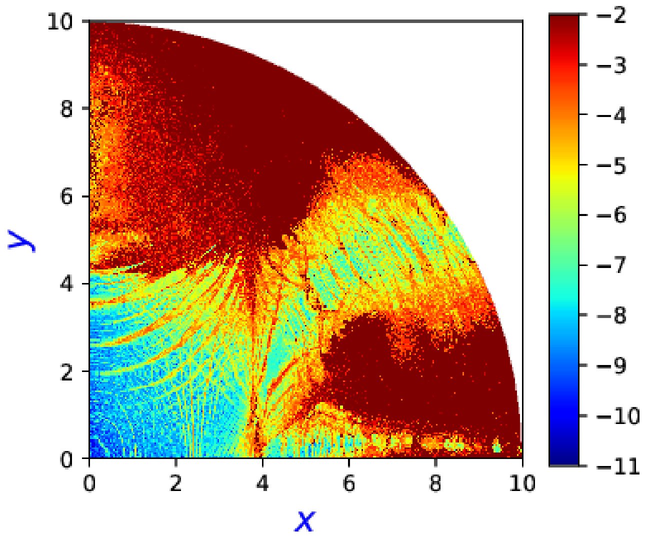


Figure 4: Horizontal and vertical spectrum for a particle with initial amplitude 1 σx, 1 σy and 1 σz with different momentum deviations. left: with crossing angle. Right: without crossing angle. The tune is (0.31,0.32)

- We can see 3rd, 4th, 5th order sum resonances are driven without the crossing angle.
- while with the crossing angle, additional 9th and 10th order sum resonances are excited, which cause a worse DA.
- with non-zero momentum deviation, synchro-betatron resonances will be excited by the presence of the crossing angle, which can reduce the DA further

- # Tune scan studies

	Smallest DA	Average DA
(0.31,0.32)	4.75	5.50
(0.19,0.17)	5.75	6.57
(0.37,0.35)	5.75	6.70
(0.12,0.13)	6.25	7.13
(0.38,0.37)	6.25	6.50
(0.24,0.26)	6.25	7.00
(0.27,0.26)	6.00	7.02
(0.17,0.19)	6.25	7.12



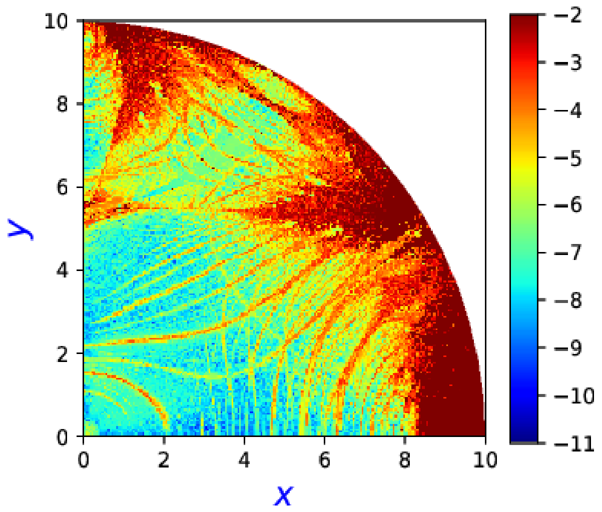


Figure 5: Amplitude space FMA plot for nominal tune (left) and a better tune (right) of (0.27, 0.26).

- The tune scan reveals there are 4 tunes where the DA increases by 1.5 σ to 7 σ and 3 others where the increase in DA is ~1 σ

- We can observe that the tune variation is smaller at the better tune.

- Different crossing angle and β*

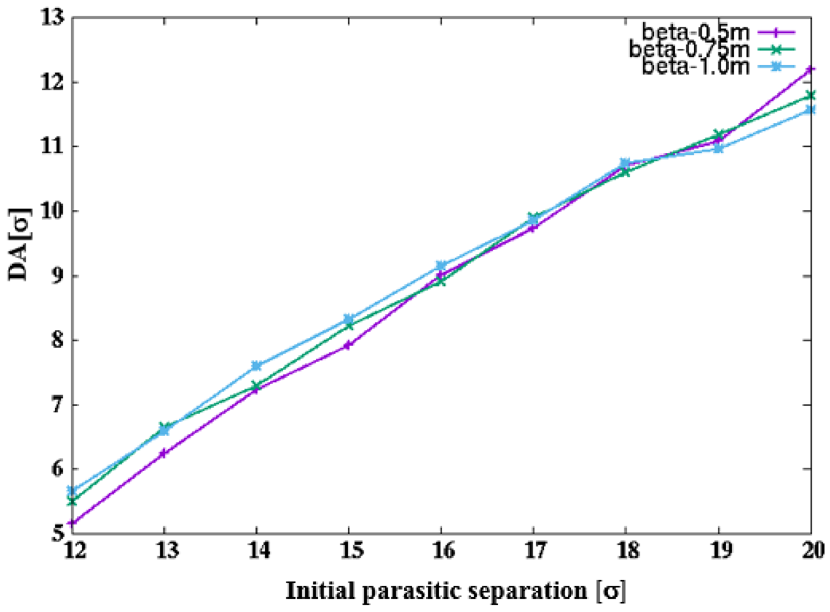
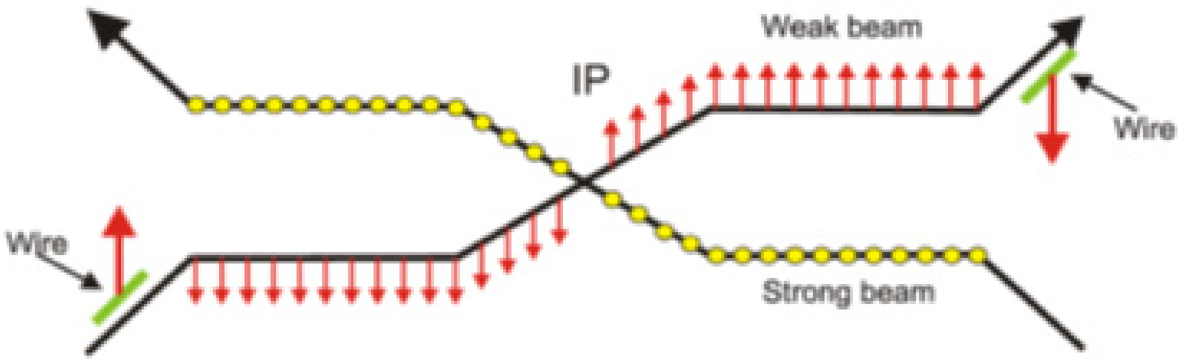


Figure 7: The DA for different β* with increasing 1st parasitic separation that is normalised by its horizontal beam size. The momentum deviation is 1 times rms momentum spread for all those cases.

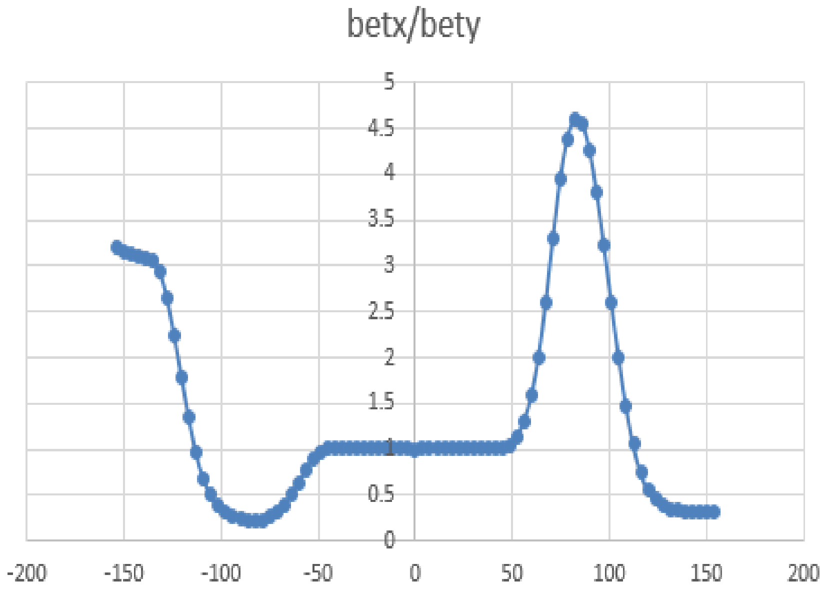
separation	Xangle[μrad] /β*=1m	Xangle[μrad] /β*=0.75m	Xangle[μrad] /β*=0.5m
12σ′	96	110	132
13σ′	104	120	144
14σ′	112	128	155
15σ′	120	138	166
16σ′	128	146	177
17σ′	136	156	188
18σ′	144	164	199
19σ′	152	174	210
20σ′	**160**	**184**	**221**

- For each β*, we find that the initial separations need to be 20 σ′ to reach the DA goal of 12 σ.
- For each β *, there is a 6 σ improvement in the DA from 12 σ′ separation to 20 σ′ separation.
- the DA is independent on β * provided the scaled separation is constant.
- the smallest physical aperture at constant initial separation of 20 σ′ is 14 σ for β*= 0.75 m and drops to 9 σ for β*= 0.5 m. This could limit β* > 0.5 m if the initial separation has to be 20 σ′.

- # Long-range interaction compensation



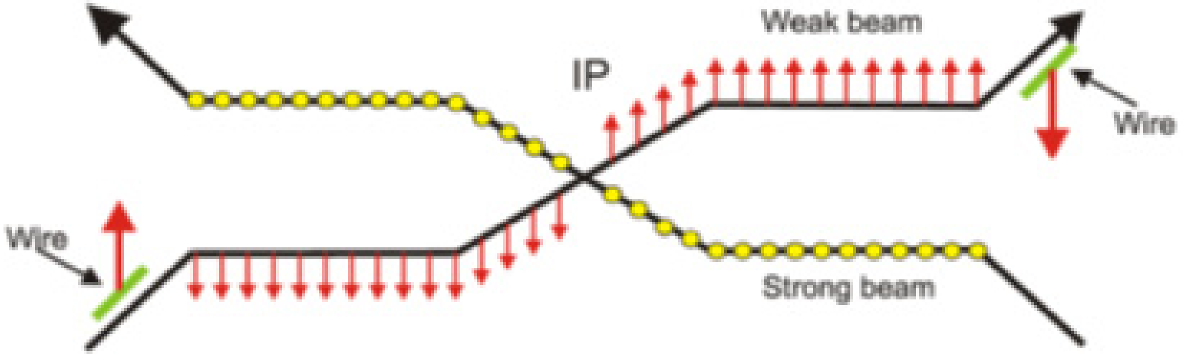
(JP Koutchouck proposed in 2000)



The βx/βy in an IR.

- **we have 4 wires distributed along the SPPC ring with one wire on each side in each IR.**
- Compensation requirements
- To compensate LRIs, When the phase advance between current wire and LRI is almost zero, the wire kick should have the opposite sign to these from the LRI but when it is π, the wire kick should have the same sign to the kick from LRIs.
- the ratio of βx/βy should match that at the long-range interaction.
- Compensation effectiveness limitation
- the phase advance between the LRIs to any place after the second separation dipole where the beam pipes are separate, is larger that 0.5π.
- this ratio varies from 1 over the first 12 of the parasitic interactions in the drift space to a high of 4.6 and a low of 0.2 over the remaining 29 interactions on one side of an IR.

- Long-range interaction compensation



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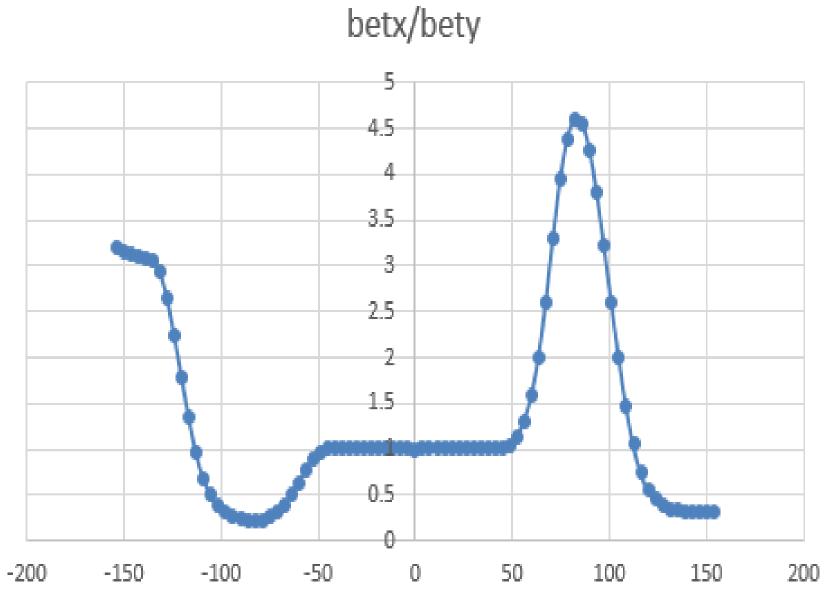


The $\beta x/\beta y$ in an IR.

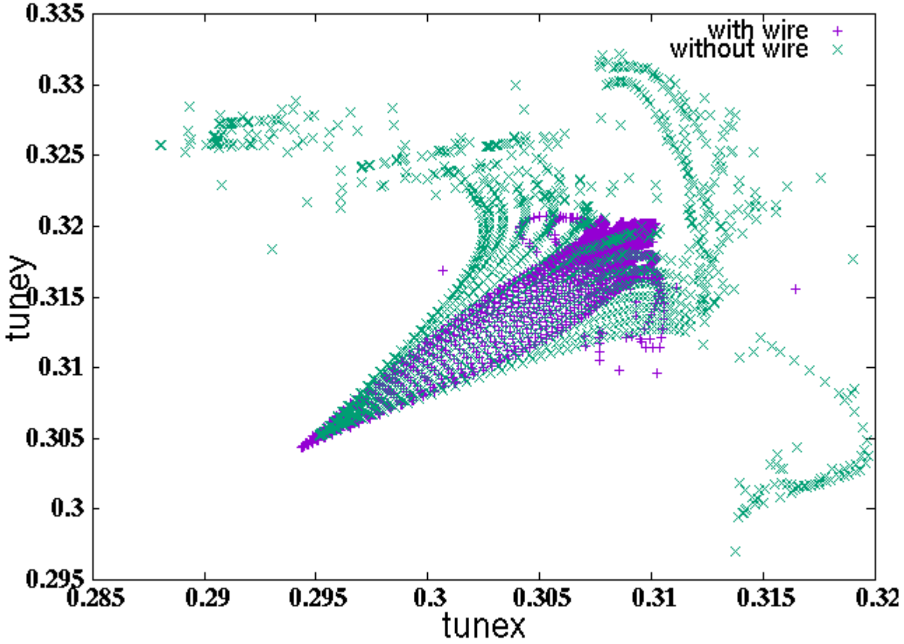
- ➢ **we have 4 wires distributed along the SPPC ring with one wire on each side in each IR.**
- ➢ Compensation requirements
- ◆ To compensate LRIs, When the phase advance between current wire and LRI is almost zero, the wire kick should have the opposite sign to these from the LRI but when it is π, the wire kick should have the same sign to the kick from LRIs.
- ◆ the ratio of $\beta x/\beta y$ should match that at the long-range interaction.
- ➢ Compensation effec

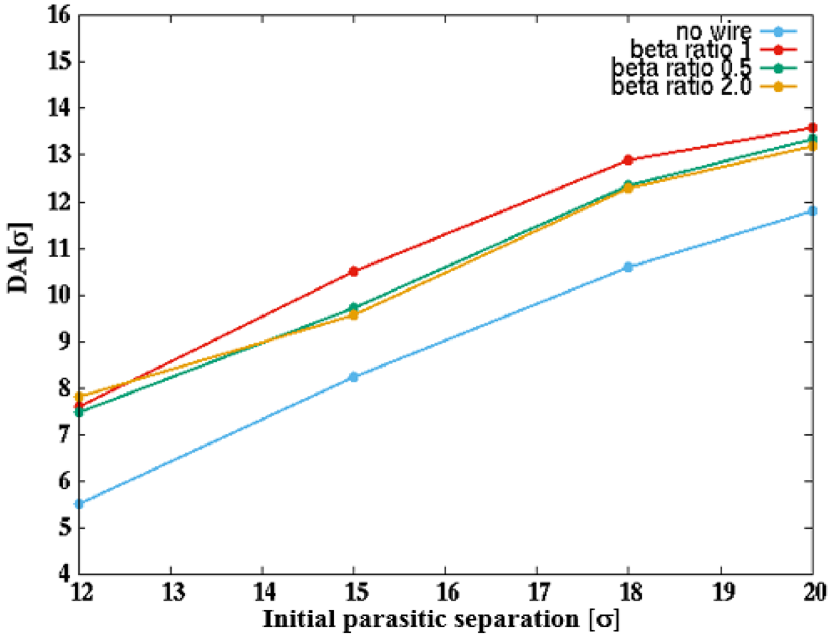
It's impossible to meet perfect compensation requirements.

- ◆ the phase advance between the LRIs to any place after the second separation dipole where the beam pipes are separate, is larger that 0.5π.
- ◆ this ratio varies from 1 over the first 12 of the parasitic interactions in the drift space to a high of 4.6 and a low of 0.2 over the remaining 29 interactions on one side of an IR.

• Long-range interaction compensation

- the ratio on the right side of the IR with horizontal crossing has values of nearly $\beta x/\beta y$ = (0.5, 1, 2).
- Antisymmetry of the optics about the IP implies that $(\beta x/\beta y)_{Right} = (\beta y/\beta x)_{Left}$.
- the phase advance of nearly π in the crossing plane
- The wires are positioned at a normalized distance identical to the initial separation.
- Compensating all the interactions requires the current in each wire to be 118.1 A.





- the tune footprint for the baseline design is significantly smaller after we use the 4 wires.
- the ratio $\beta x/\beta y = 1$ leads to the largest DA.
- Considering the antisymmetry of the optics, when the beta ratio is either 2 or 0.5, the DA is about the same.
- there’s a 2 σ increase in the DA with the wire compensation.

Conclusion

- long-range interactions are the main factor limiting particle stability and the DA in the SPPC baseline design is only 5.5 σ.

- Tune scans showed that the beam-beam interactions strongly excite the 3rd, 4th, 5th, 9th and 10th order sum resonances, the latter two in the presence of the crossing angles. The DA can be improved by ~1.5 σ with different choices of tunes.

- To reach the DA goal of 12 σ, increasing the crossing angle or increasing β^* are the most useful options.

- the optimal location for the wires is at a phase advance of π from the long-range interactions in the crossing plane and where $\beta x/\beta y = 1$. At these locations the wires increase the DA by 2 σ over a large range of crossing angles.

The present studies don't include the magnetic errors, especially the nonlinearity of Inner Triplet(IT),
When we have all of those nonlinearities, the DA simulation have to be redone.