Beam blowup due to synchro-beta resonance with/without beam-beam effects

K. Oide, D. El Khechen (CERN)

Many thanks to M. Benedikt, D. Shatilov, F. Zimmermann, and the entire FCC-ee Collaboration Team

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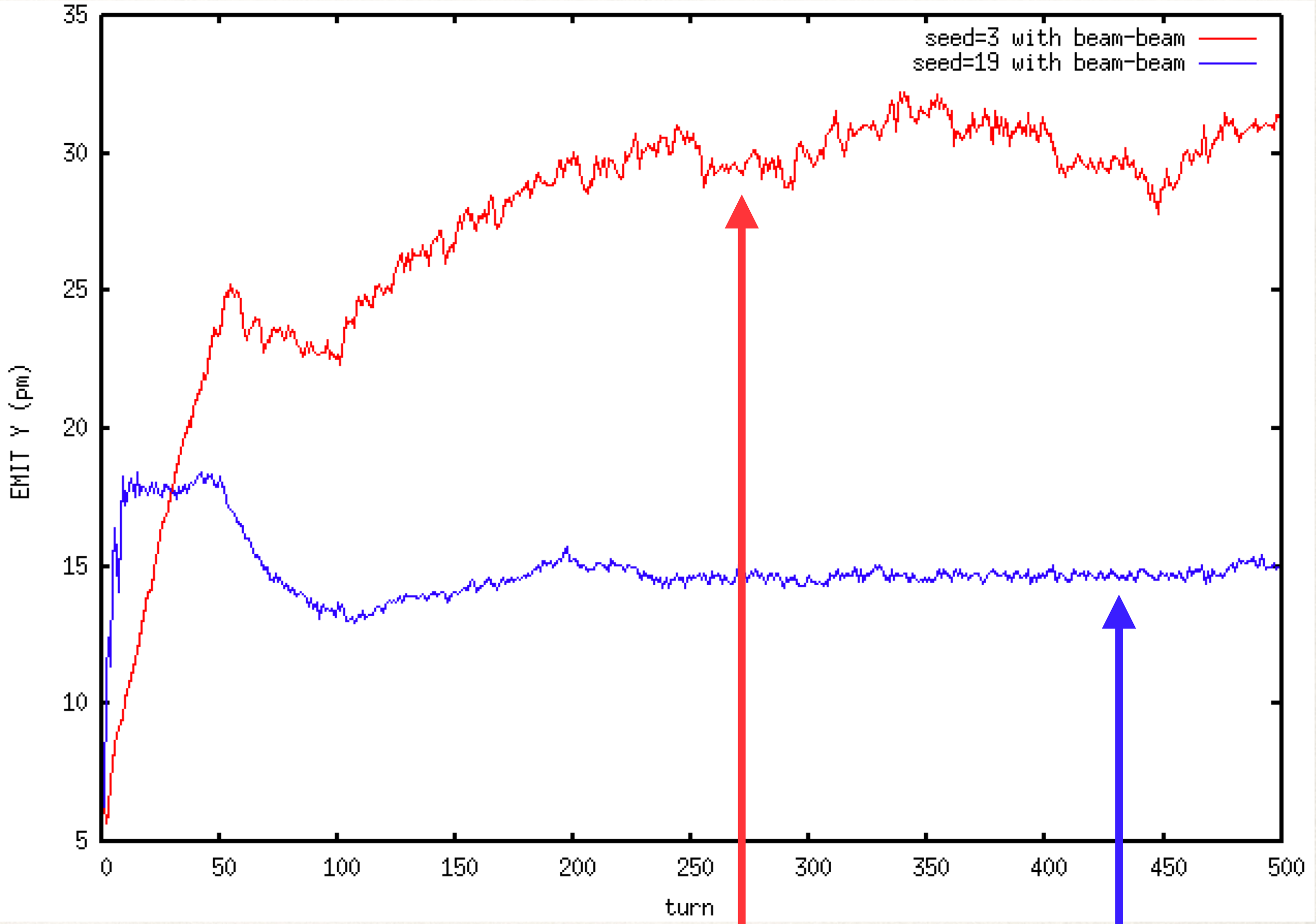
Unexpected beam blowup

- D. El Khechen has observed an unexpected vertical beam blowup in tracking simulations with beam-beam and lattice for FCC-ee ttbar by SAD.
- The vertical (on closed orbit) emittance of the lattice is generated by random misalignments of sextpoles and set to the design (2.9 pm = 0.2%).
- In early simulations with beam beam and lattice without misalignment did not show such blowups (D. Zhou).
- The blowup strongly depends on the random number for strength of skew quads or misalignments of sextupoles to produce the vertical emittance.



Coupling (%)	0.2	0.2
RMS of sext. Offset ()	11	15
Seed	3	19
η_y @ (IP.1, IP.2) ()	(-5.3, 4.24)	(-8.9,8)
$\eta_{py} \times \beta_y^*$ @ (IP.1, IP.2) ()	(6.8, 1.04)	(35.4,23)
R2 parameter	$(1.8\times10^{-3},1.8\times10^{-3})$	$(-5.1\times10^{-5},-1.8\times10^{-4})$

lattice emittance on closed orbit = 2.9 pm

D. El Khechen

Why unexpected?

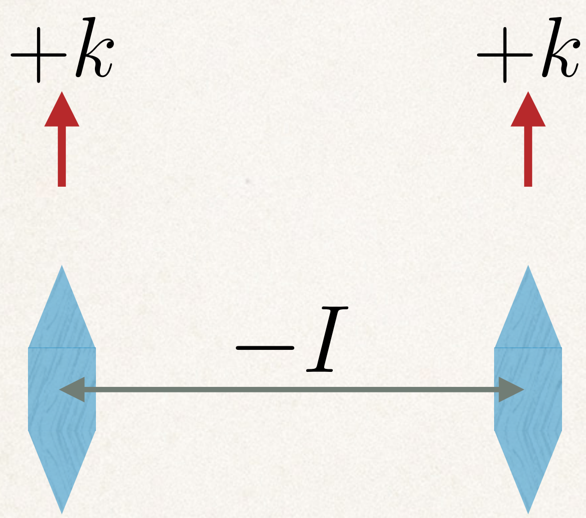
- This unexpected blowup occurs even when the residual dispersion at the IP is below the criteria given by D. Shatilov with beam-beam simulation with beamstrahlung but without the lattice.

		45.6	80	120	175
	Energy [GeV]	45.6	80	120	175
	Vertical beam size (nominal) [μ]	0.028	0.041	0.035	0.066
	Energy spread (with BS)	$1.3\cdot10^{-3}$	$1.3\cdot10^{-3}$	$1.65\cdot10^{-3}$	$1.85\cdot10^{-3}$
w/o BS	Dispersion for +5% in σ_y [μ]	7	10	7	11
with BS	Actual σ_y/σ_{y0} with such a dispersion	2.7	1.18	1.16	1.17
with BS	Actual dispersion for +5% in σ_y [μ]	1	5	4	6

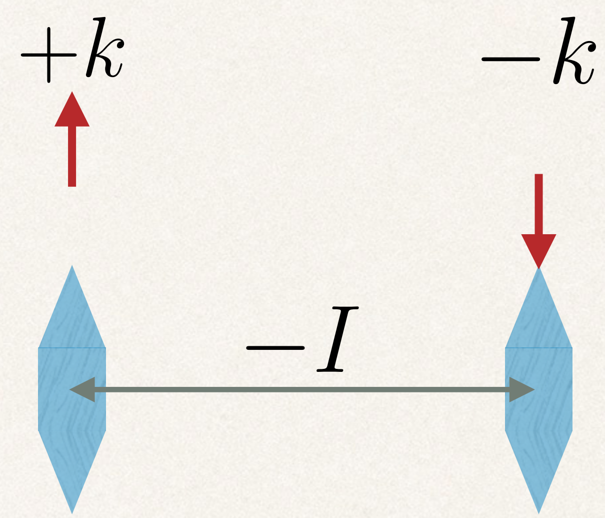
D. Shatilov

Method

- Lattice: FCCee_t_217_nosol_2.sad, 182.5 GeV, half ring.
- The vertical emittance is given by randomly excited skew quadrupole placed on each sextupole in the arc:



Symmetric: vertical dispersion is confined within the pair, x-y coupling leaks outside.



Antisymmetric: x-y coupling is confined within the pair, vertical dispersion leaks outside.

- The vertical invariant emittance is always set to 2.9 pm ($\varepsilon_y / \varepsilon_x = 0.2\%$).
- Synchrotron radiation in all magnets.
- Tapering.
- Optionally, simplified beam-beam effects and beamstrahlung can be applied.
- 1000 particles up to 300 half-turns.

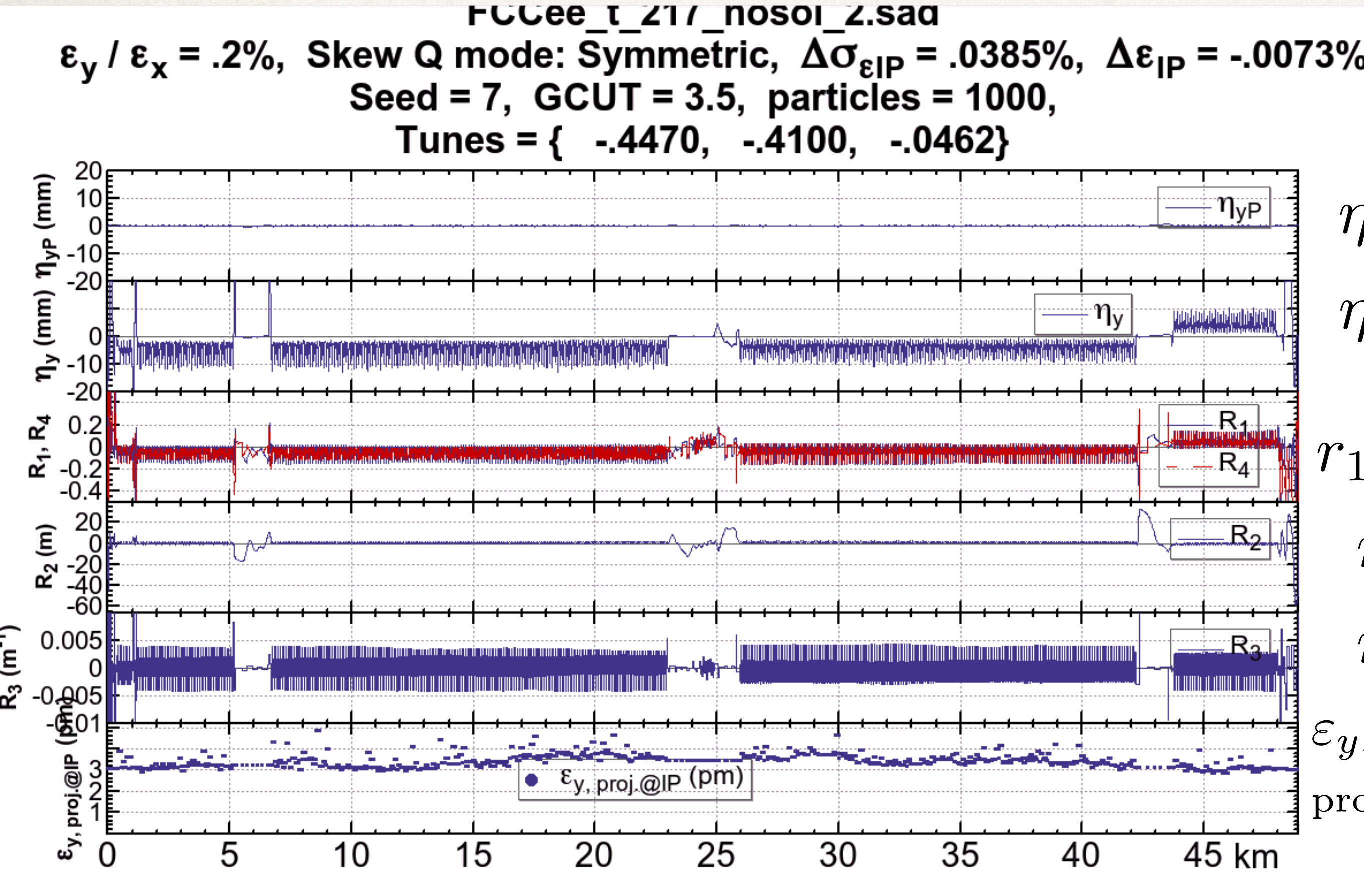
Optics by different excitations of skew quads

Symmetric Skew Quads

Vertical dispersion is confined within the pair, x-y coupling leaks outside.

Antisymmetric Skew Quads

X-y coupling is confined within the pair, vertical dispersion leaks outside.



η_y

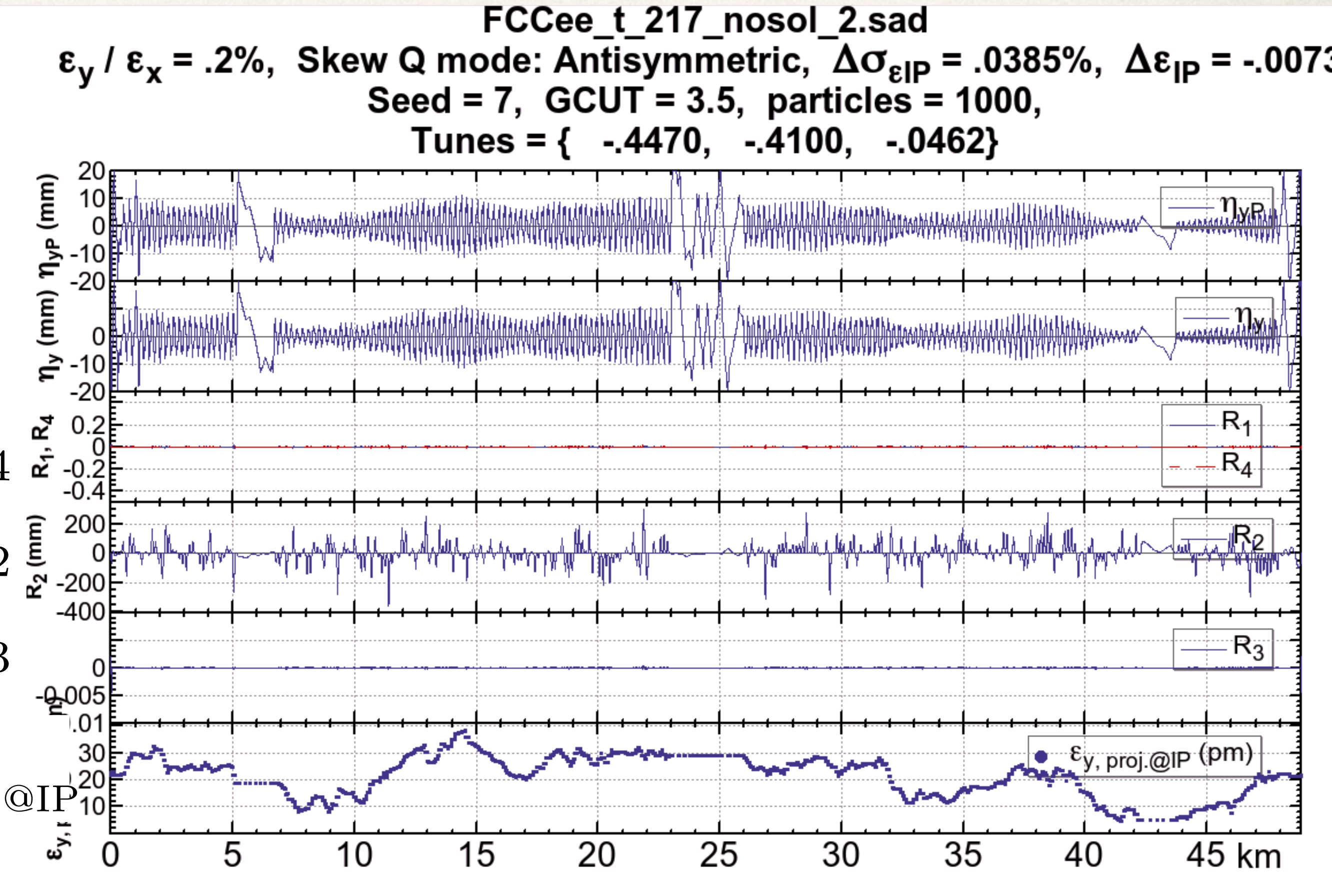
η_v

$r_{1,4}$

r_2

r_3

ε_y, proj.@IP



definition of x-y coupling parameter:

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \mathrm{R} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} = \begin{pmatrix} \mu & . & -r_4 & r_2 \\ . & \mu & r_3 & -r_1 \\ r_1 & r_2 & \mu & . \\ r_3 & r_4 & . & \mu \end{pmatrix} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix},$$

betatron coordinate

physical coordinate

The skew quads on a sextupole pair can be represented by two random numbers $k_{1,2}$ and a parameter $-1 \leq s \leq 1$ as $(k_1 + sk_2, k_2 + sk_1)$. Then

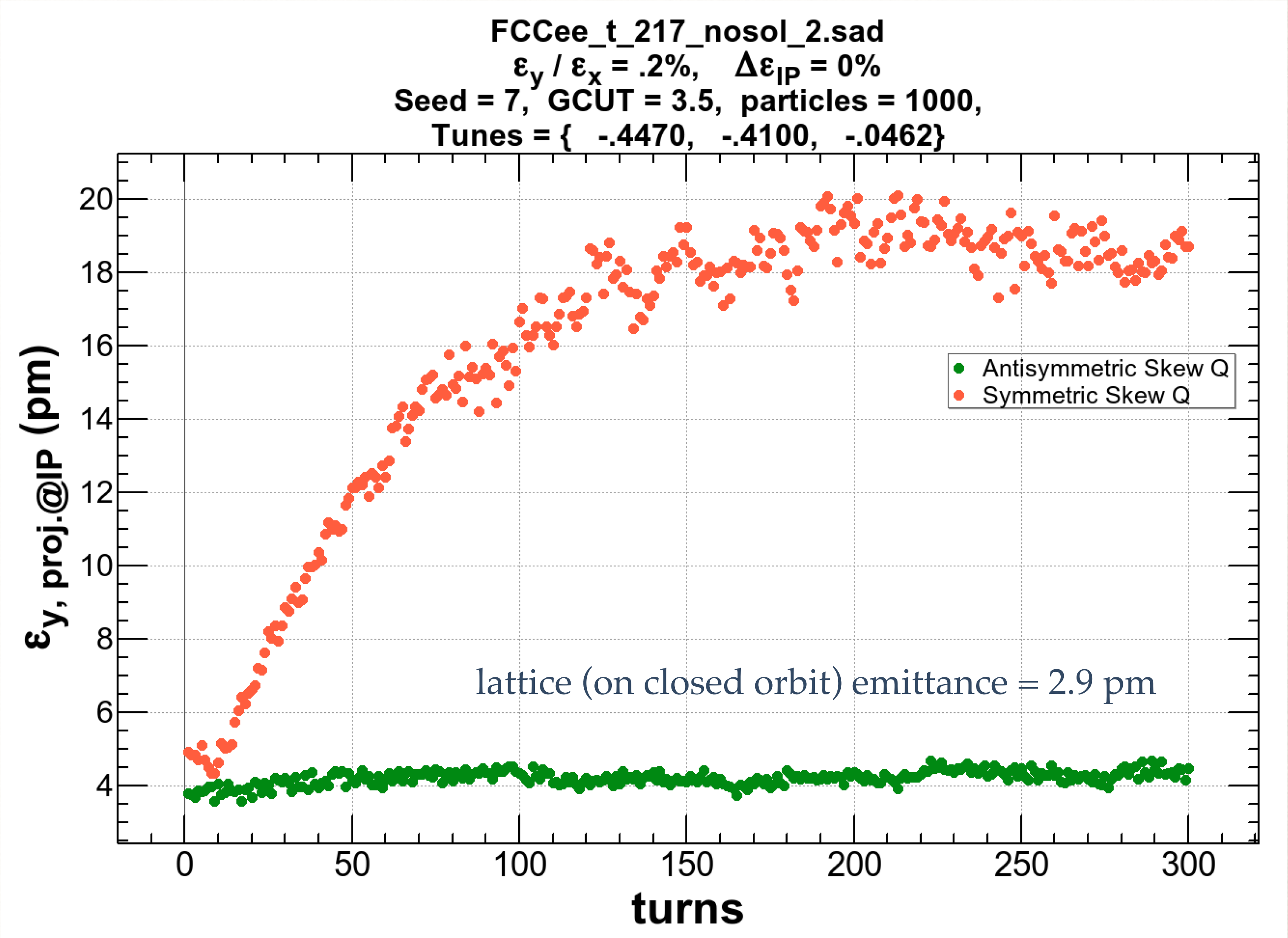
$s = 1$: perfect symmetric

$s = -1$: perfect antisymmetric

$s = 0$: : simply random

Unexpected beam blowup

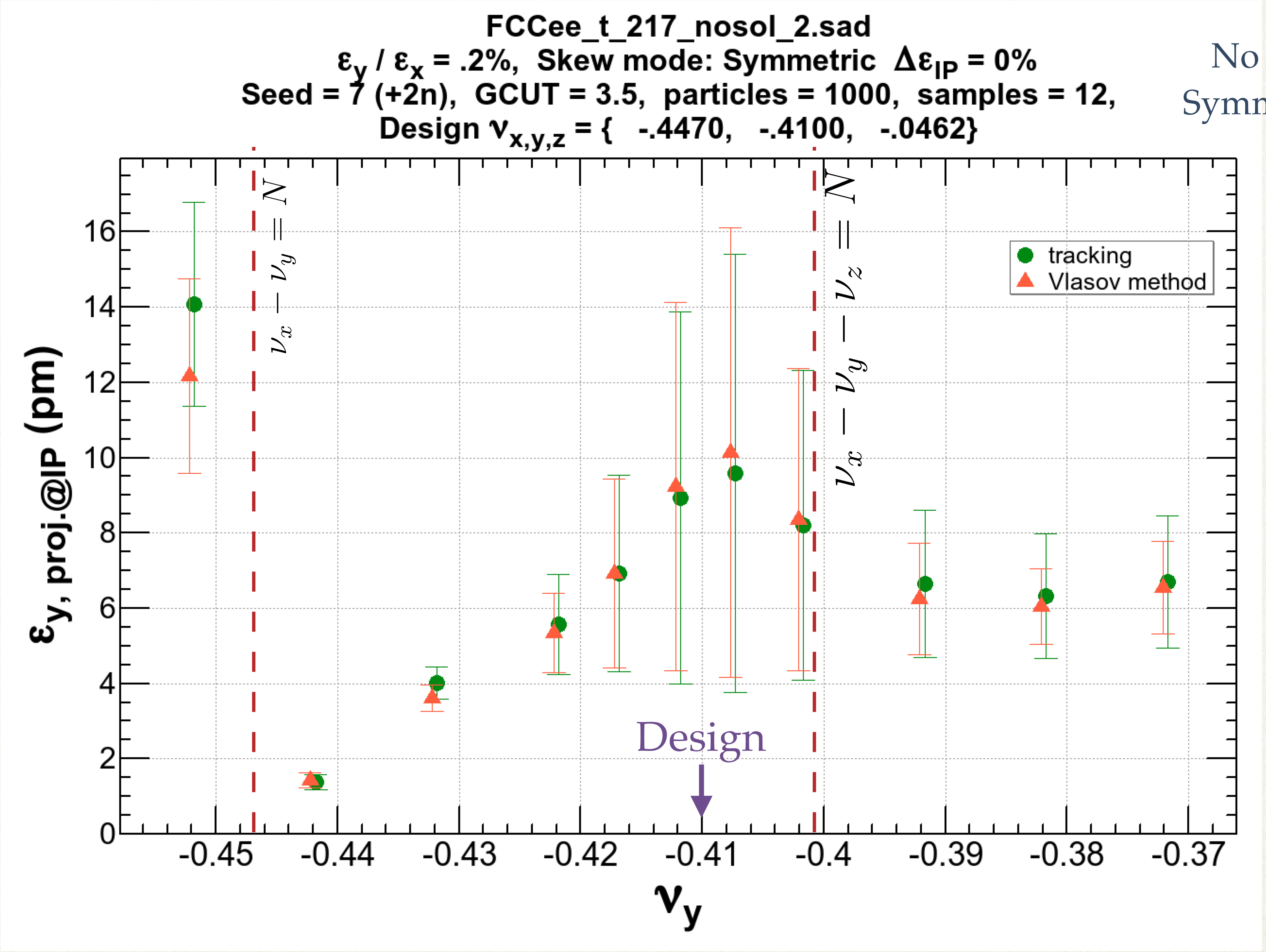
- Then it was found that such a blowup could occur even ***without beam-beam***.
- The blowup depends on how the vertical emittance is generated (between symmetric skew = *x*-*y* coupling dominated and antisymmetric skew = vertical dispersion dominated).
- The blowup is explained by a Vlasov model for "anomalous emittance" in Ref. [2]. .



[2] K. Oide, H. Koiso, ``Anomalous equilibrium emittance due to chromaticity in electron storage rings'', Phys.Rev. E49 (1994) 4474-4479.

The Vlasov model agrees with tracking

No beam-beam
Symmetric Skew Q



- The error bars show the variation for 12 samples of skew excitations.
- The most significant resonance is $\nu_x - \nu_y - \nu_z = N$, according to the tune dependence.

The Vlasov model (in Ref. [2])

We define the mean value $\mathbf{h}$ of the orbit deviation from the transverse part of $\mathbf{x}_e$ and the transverse variance matrix W around $\mathbf{h}$ as

$$\mathbf{h}(J_z,\phi_z)=\int(\mathbf{x}_t-\mathbf{x}_{te})f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t/\rho(J_z)\ ,$$
$$W(J_z,\phi_z)=\int(\mathbf{x}_t-\mathbf{x}_{te})(\mathbf{x}_t^T-\mathbf{x}_{te}^T)\times f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t/\rho(J_z)\ , \tag{3}$$

where f is the six-dimensional distribution function at s, and the integration is performed over the transverse phase space. The subscript t indicates the transverse part. The longitudinal distribution $\rho(J_z)$ is Gaussian, i.e.,

$$\int f(\mathbf{x}_t,J_z,\phi_z)d\mathbf{x}_t=\rho(J_z)=\exp(-J_z/\sigma_\delta^2)/\sigma_\delta^2\ , \tag{4}$$

where σ_δ is the momentum spread. Since we have assumed that the synchrotron motion is sinusoidal, which advances the phase ϕ_z by μ_z in one revolution of the ring as Eq. (2), the equilibrium distribution satisfies these equations:

$$\mathbf{h}(J_z,\phi_z+\mu_z)=U\mathbf{h}(J_z,\phi_z)+\mathbf{d}+\Delta\mathbf{h}\ ,$$
$$W(J_z,\phi_z+\mu_z)=UW(J_z,\phi_z)U^T+\mathbf{d}\mathbf{h}^TU^T+U\mathbf{h}\mathbf{d}^T+\mathbf{d}\mathbf{d}^T+D+\Delta W\ , \tag{5}$$

Closed orbit (J_z, ϕ_z)

Transverse second moment (J_z, ϕ_z)

The longitudinal distribution is Gaussian

$U=U(\delta)$: momentum dependent 1-turn xfer matrix

Equilibrium after one revolution of the ring

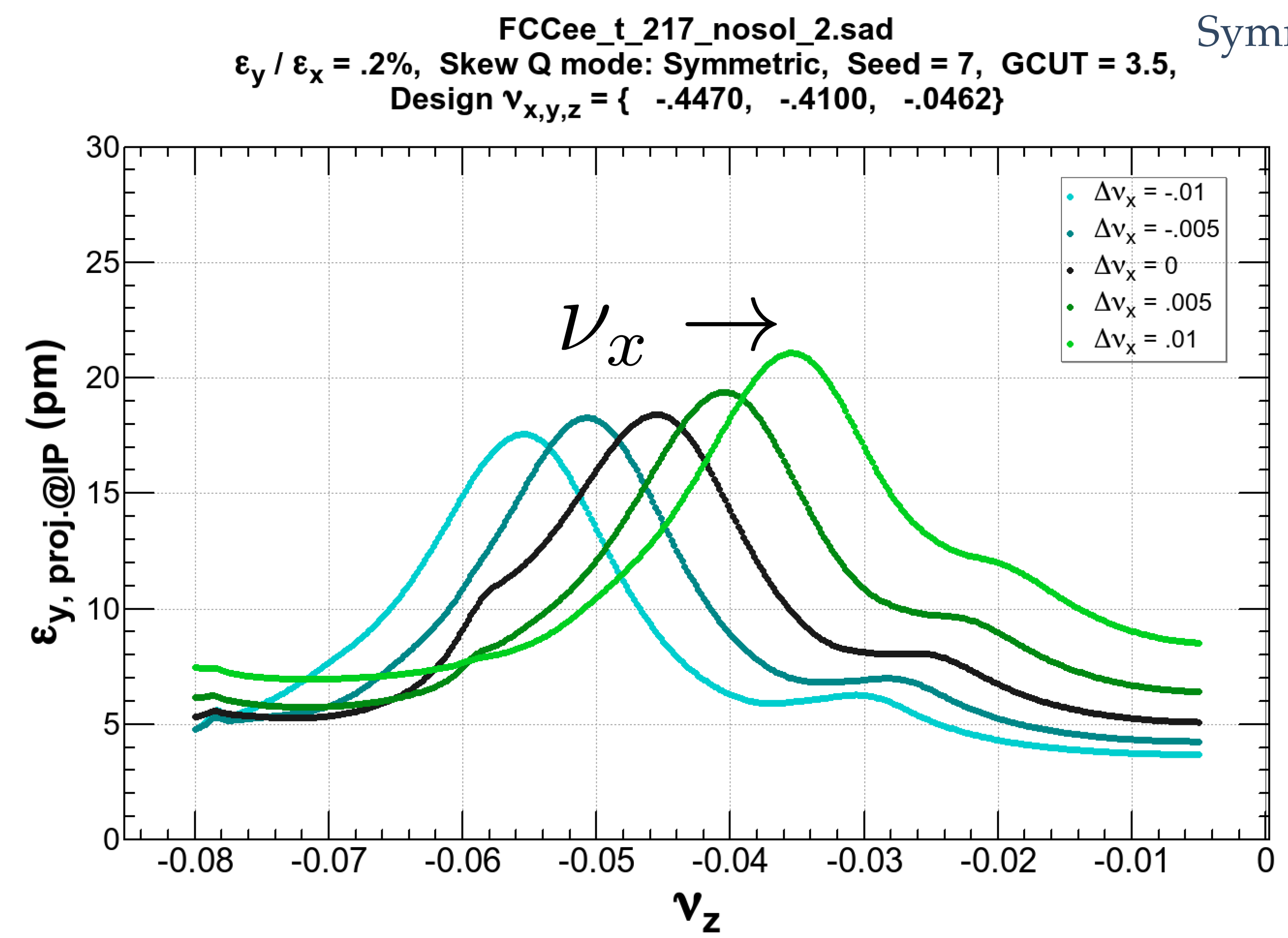
Diffusion is also taken into account.

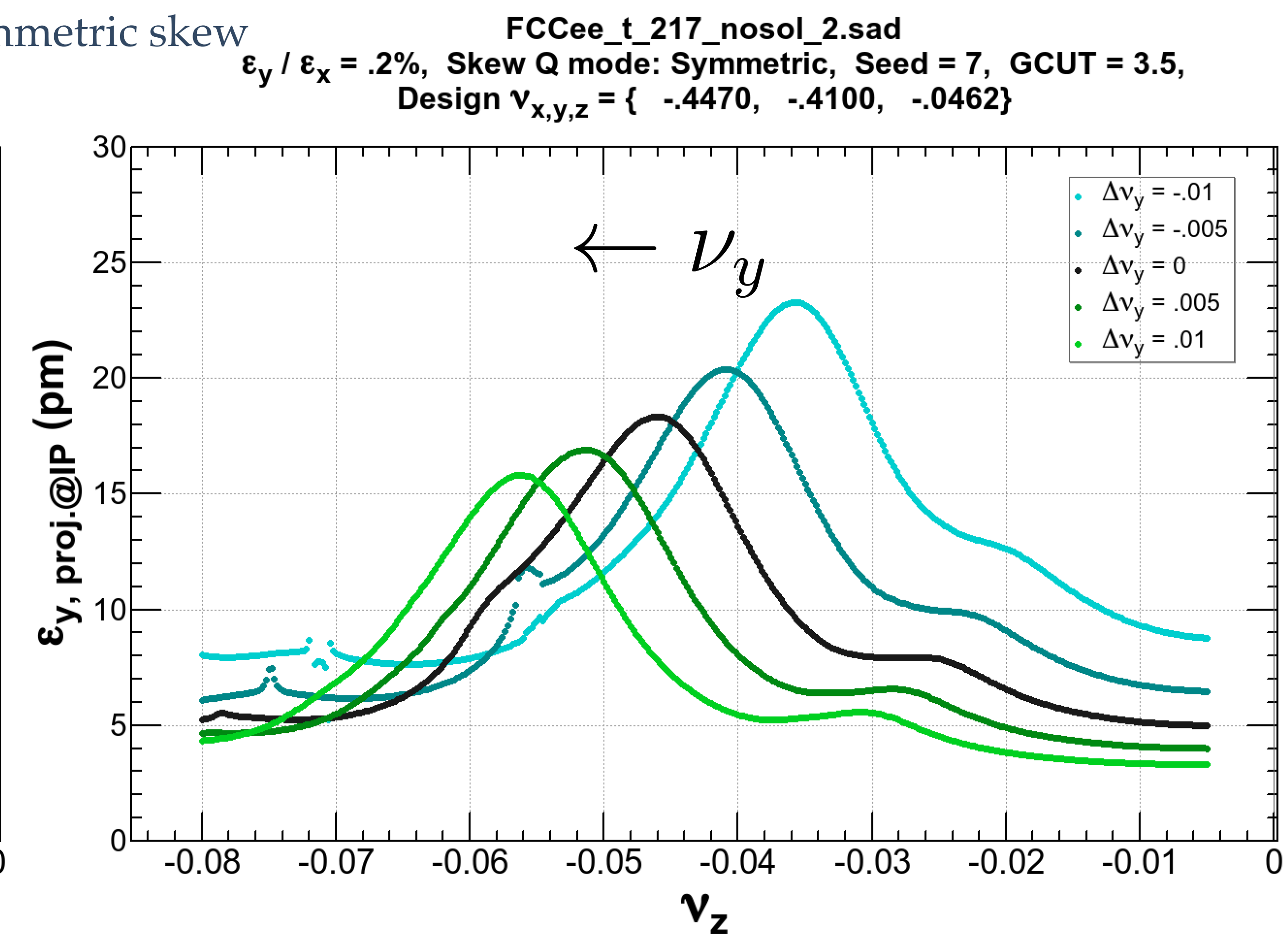
Tune dependence by Vlasov model

- As the agreement with tracking looks excellent, let us use the Vlasov model hereafter, since it is many orders faster than tracking.
- Scanning the synchrotron tune is just easy in the model, since it is just a parameter and no change in the lattice is necessary.

No beam-beam

Symmetric skew



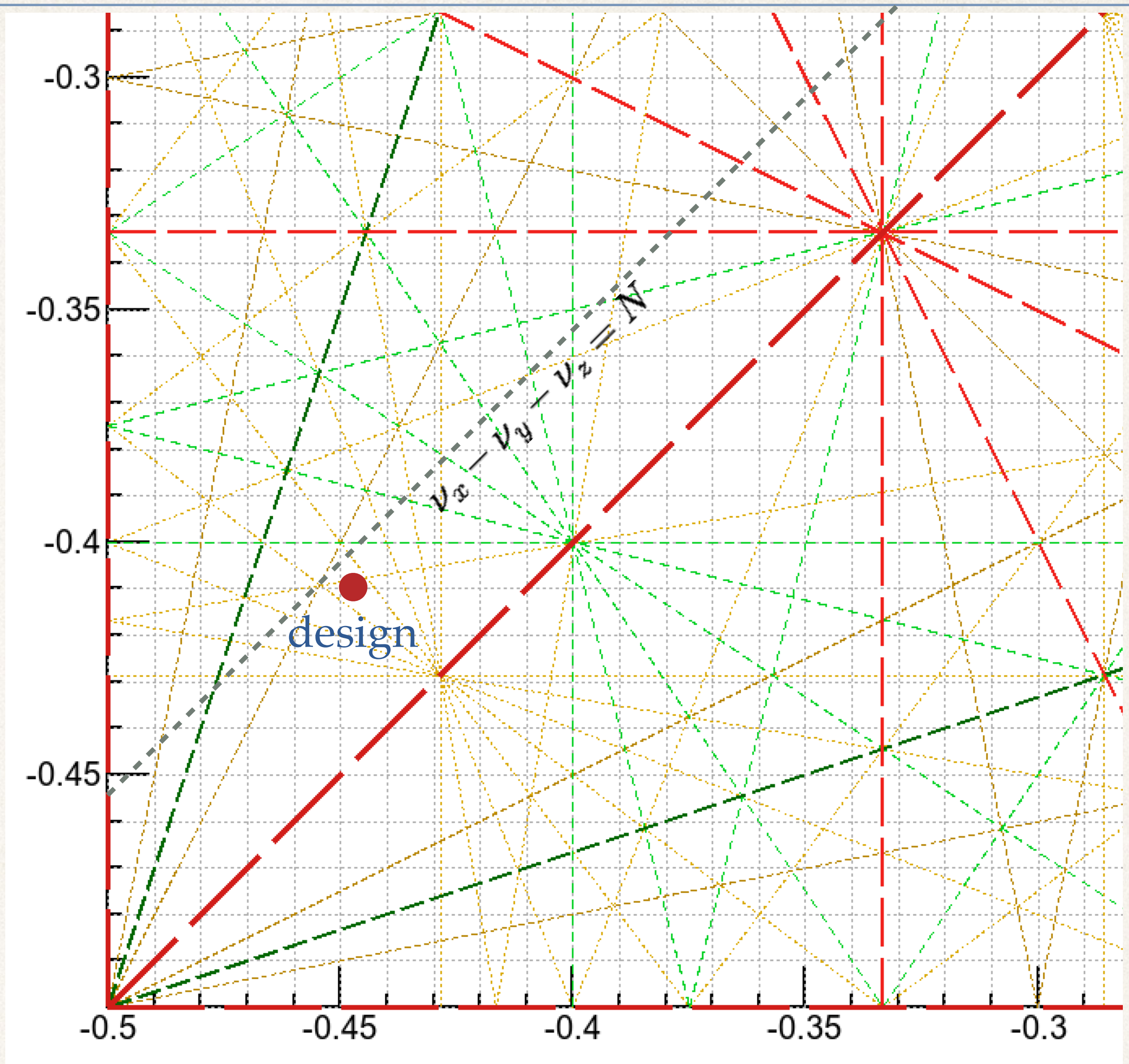


- The width of resonance ~ damping rate = 1/(40 half turns)

Skew Q is fixed at the design νz in these figures above.

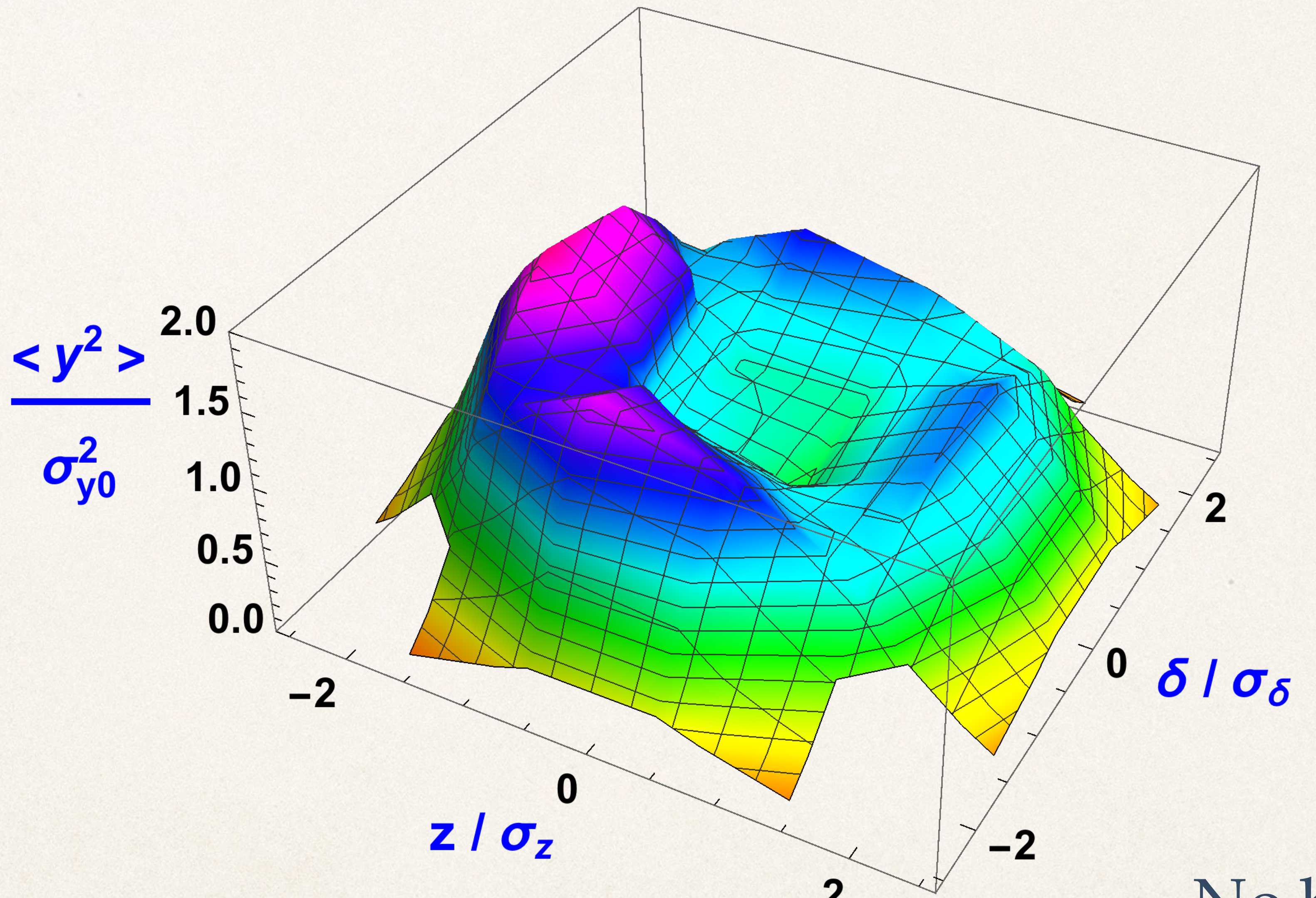
- According to the tune dependence above, the resonance $\nu_x - \nu_y - \nu_z = N$ is identified as the most relevant one.

The resonance line



- The design tune point is a little bit off the resonance line — but it has a meaning: the blowup can be larger than on a tune exact at the resonance.

The Vlasov model

- Near a resonance line, the transfer matrix over one synchrotron period can be on resonance at a certain amplitude of the synchrotron motion. This leads to the anomalous beam blowup.
- 

No beam-beam
Symmetric skew

Implementation of simplified beam-beam

- The beam-beam tune shift and beamstrahlung can be implemented in the Vlasov model, by introducing a thin kick

$$\Delta p_{x,y} = -k\frac{\partial U}{\partial(x,y)} \ , \tag{1}$$

where U is a potential by a gaussian charge distribution.

- The associated transfer matrix is

$$M_{\mathrm{BB}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -k\frac{\partial^2 U}{\partial x^2} & 1 & -k\frac{\partial^2 U}{\partial x \partial y} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -k\frac{\partial^2 U}{\partial x \partial y} & 0 & -k\frac{\partial^2 U}{\partial y^2} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} , \tag{2}$$

where k and U are chosen to the matrix be consistent with beam-beam parameters $\xi_{x,y}$.

- Beamstrahlung is simplified by an excitation matrix

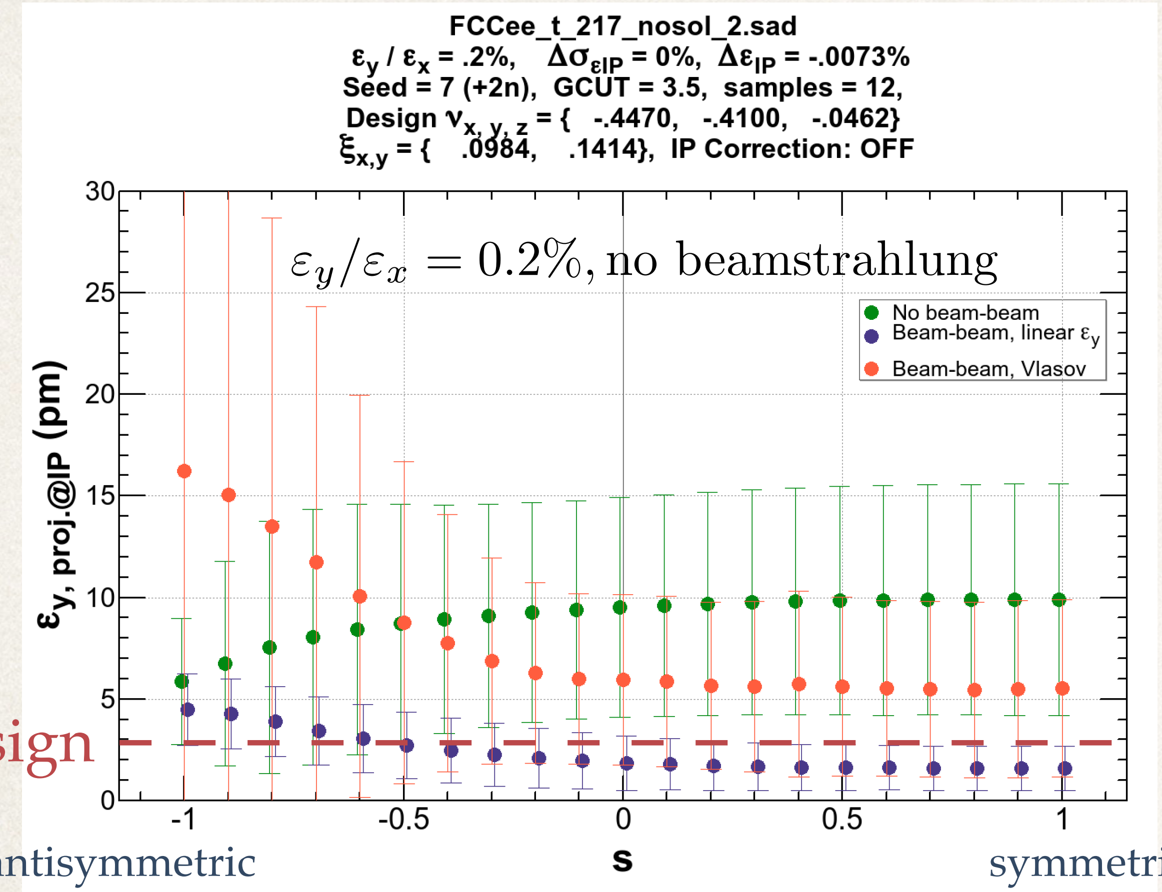
$$\Delta\Sigma_{\mathrm{BB}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Delta\sigma_\varepsilon^2 \end{pmatrix} , \tag{3}$$

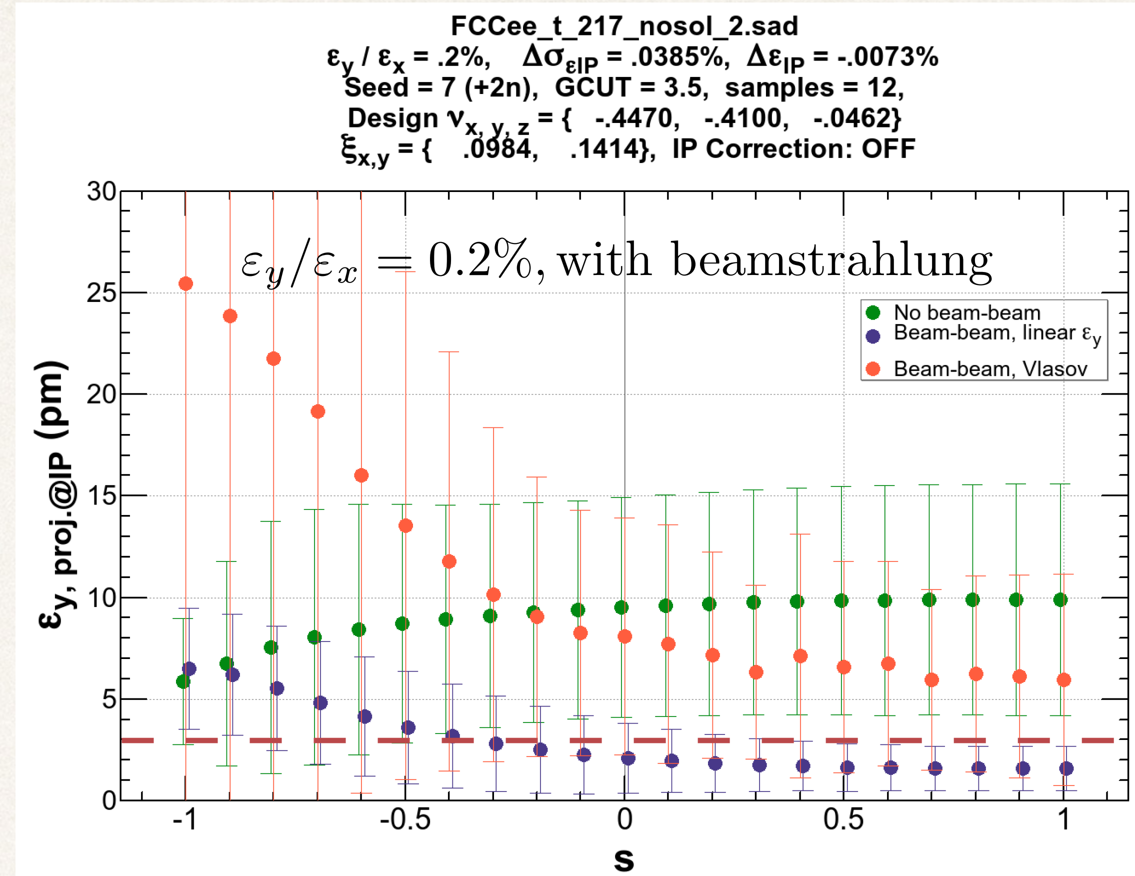
where σ_ε is the single-pass energy spread due to beamstrahlung.

The damping due to BS is also implemented in a similar way.

- In the case of FCC-ee@182.5 GeV, $\xi_{x,y} = (0.0984, 0.1414)$ and $\sigma_\varepsilon = 3.85 \times 10^{-4}$.

Blowup with/without beam-beam

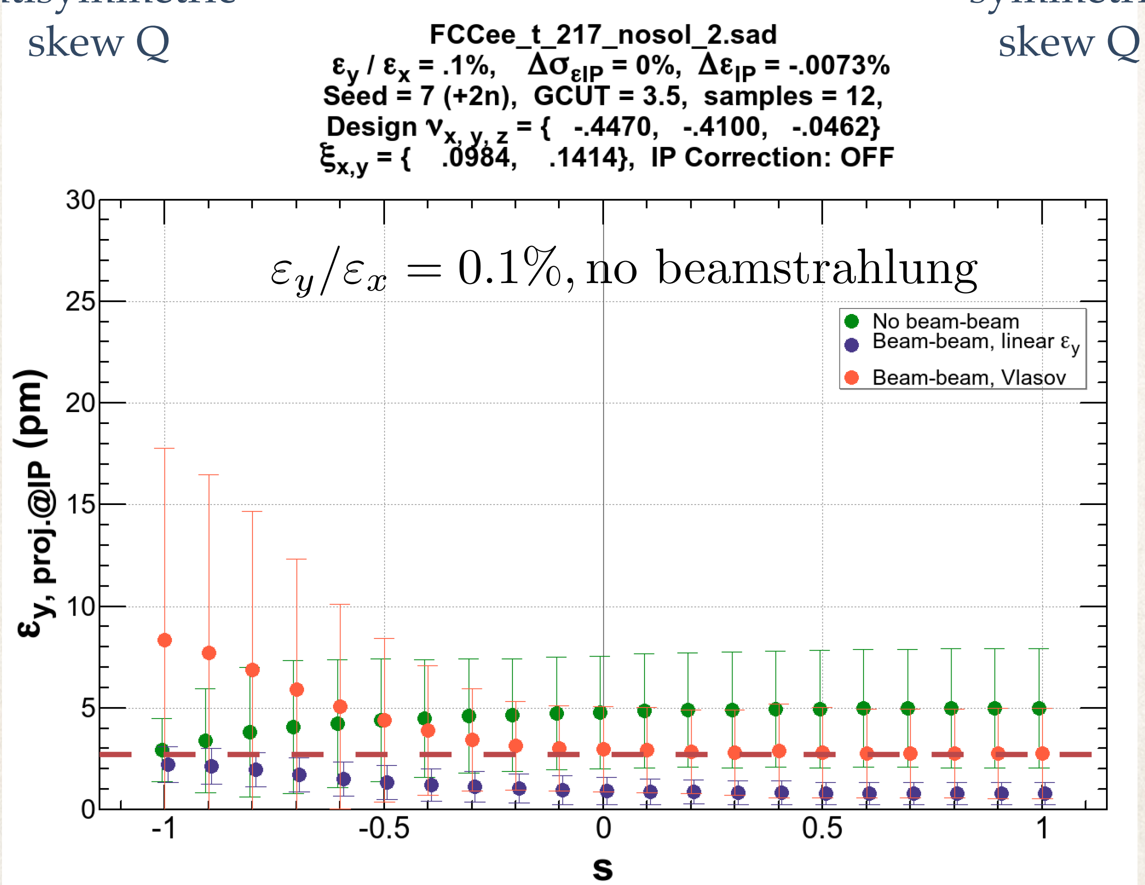


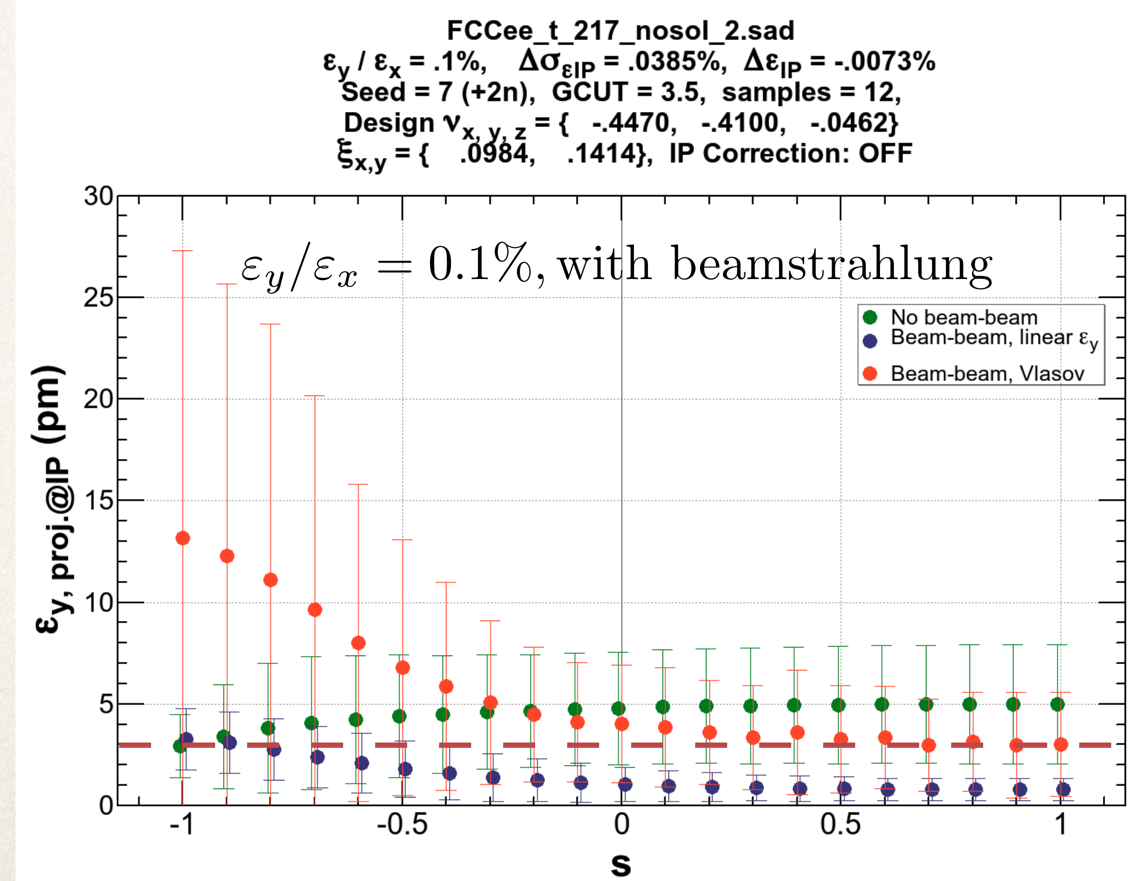


design

antisymmetric skew Q

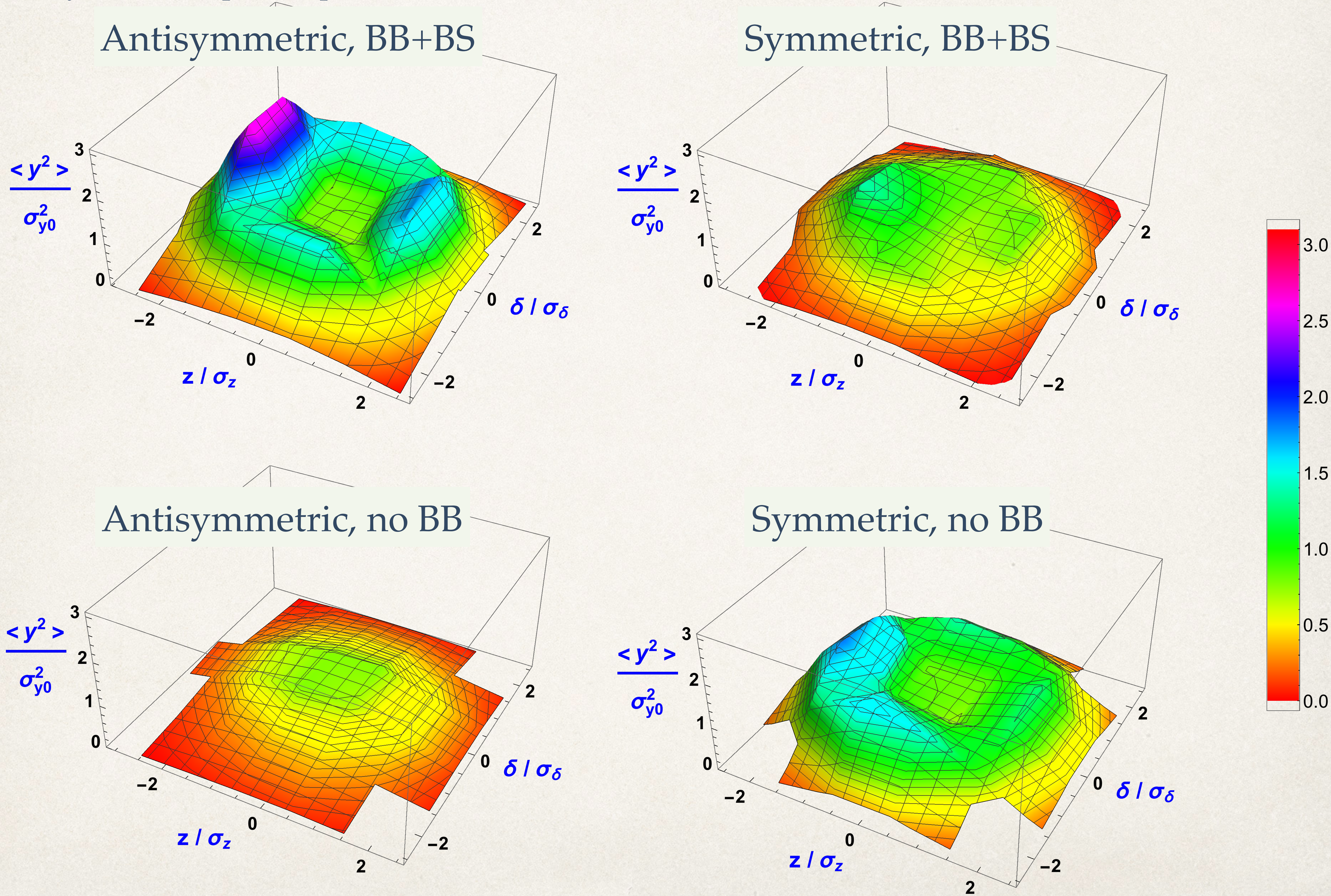
symmetric skew Q





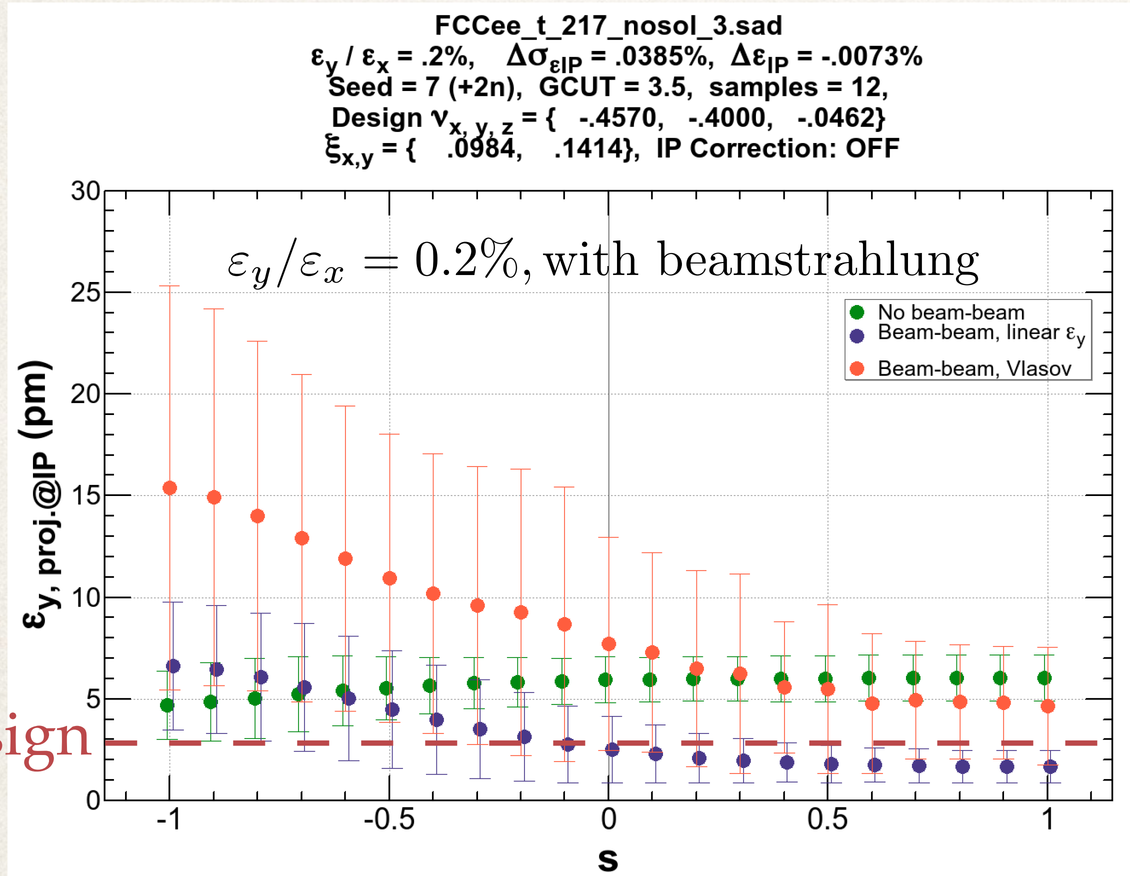
Comparison of the blowups

in the synchrotron phase space



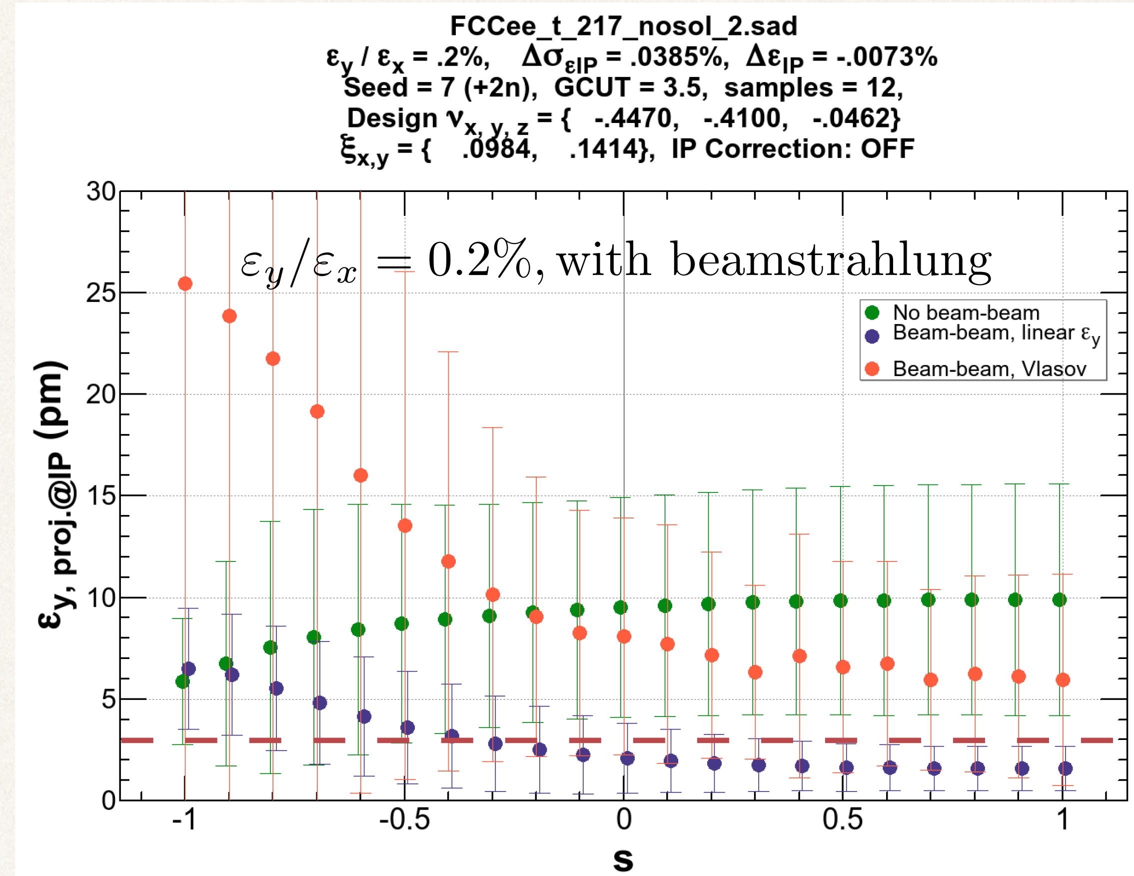
An alternative tune

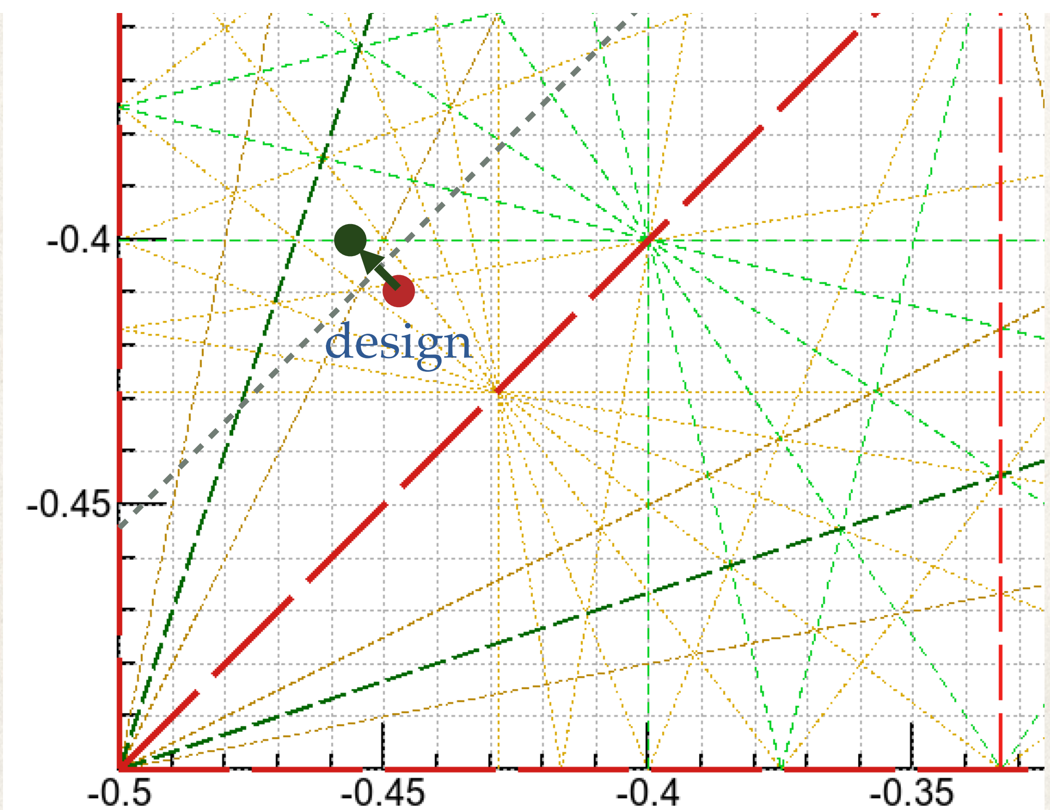
An alternative tune



design

Design tune





Shifting the tune by $\Delta\nu_{x,y} = (-0.01, 0.01)$ relaxes the blowup. Combining with a lower emittance may reduce the blowup within the design emittance.

How can we solve the unexpected beam blowup?

- The unexpected (anomalous) emittance blowup sets an additional condition for the machine.
- Not only the luminosity, but beam losses, detector background, quenches of superconducting magnets will be affected.
- Probably the most straight-forward solution is to reduce the lattice (on closed orbit) emittance well below the design. For instance it should be less than 0.1% in the case of FCC-ee ttbar.
- Such a very small emittance is reachable by the emittance tuning method simulated.
- Once such a very small vertical emittance is achieved, a question is how to blowup it to the design value. For that purpose an emittance control knob, which does not affect the anomalous emittance, must be developed.

Summary

- Unexpected blowups of the vertical emittance have been seen in tracking in lattices for FCC-ee with skew quads or vertical misalignments of sextupoles, with or without beam-beam.
- This effect is well explained by a Vlasov model of the transverse distribution in the longitudinal phase space.
- The effect is a synchrotron-betatron resonance depending on the synchrotron oscillation amplitude.
- This effect sets another criteria on the machine tuning and alignment tolerances.
- Even smaller vertical emittance of the lattice will be necessary to achieve the desired emittance.

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- Unexpected blowups of the vertical emittance have been seen in tracking in lattices for FCC-ee with skew quads or vertical misalignments of sextupoles, with or without beam-beam.

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- This effect sets another criteria on the machine tuning and alignment tolerances.

- Even smaller vertical emittance of the lattice will be necessary to achieve the desired emittance.

Thank you for paying attention!

Backups

Luminosity performance

Table 2.1: Machine parameters of the FCC-ee for different beam energies.

		Z	WW	ZH	$t\bar{t}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[1]	3396[??]
Bunch population	$[10^{11}]$	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60		90/90		
Momentum compaction α_p	$[10^{-6}]$	14.8		7.3		
Arc sextupole families		208		292		
Horizontal β^*_x	[m]	0.15	0.2	0.3	1.0	
Vertical β^*_y	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ^*_x	[µm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ^*_y	[nm]	28	41	36	66	68
Energy spread (SR/BS) σ_δ	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS)		8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Length of interaction area L_i	[mm]	0.42	0.85	0.90	1.8	1.8
Hourglass factor R_{HG}						
Crab sextupole strength	[%]	97	87	80	40	40
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Synchrotron tune Q_s		0.0250	0.0506	0.0358	0.0818	0.0872
Long. damping time	[turns]	1273	236	70.3	23.1	20.4
RF acceptance	[%]	1.9	3.5	2.3	3.36	3.36
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.4	
Polarisation time t_p	[min]	15000	900	120	18.0	14.6
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.108	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.113	0.016/0.118	0.097/0.128	0.099/0.126
Allowable e^+e^- charge asymmetry	[%]	±5	±3			
Lifetime by rad. Bhabha	[min]	68	59	38	40	39
Actual lifetime by BS	[min]	> 200	> 200	18	24	18

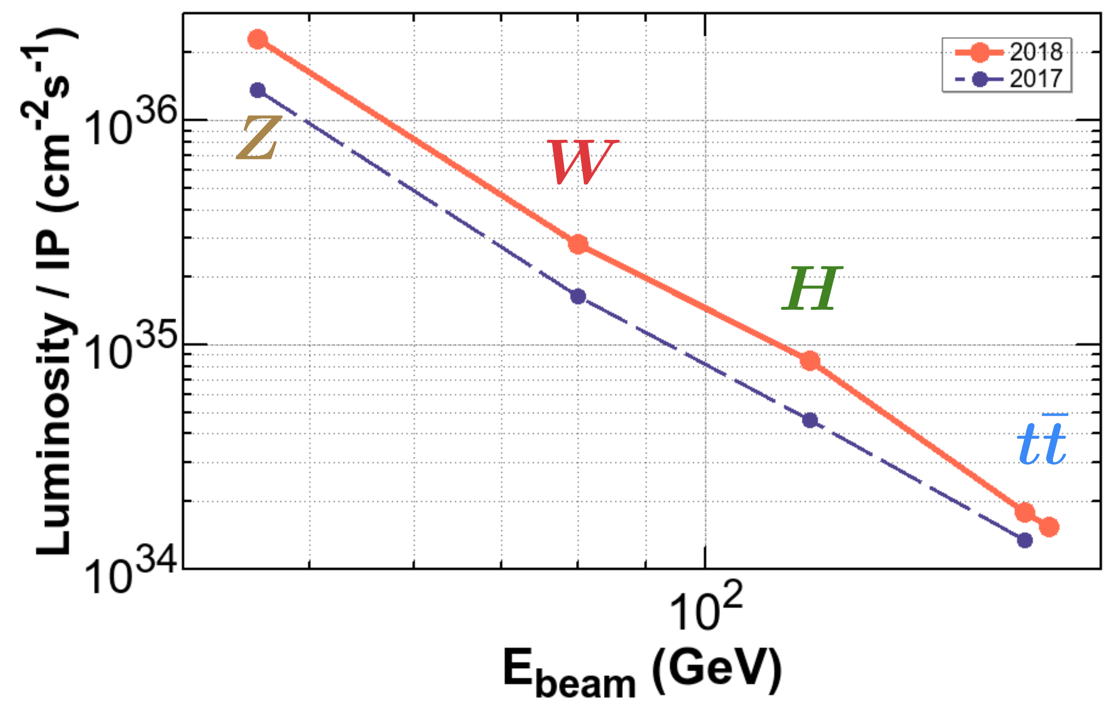

Table 2.10: Peak luminosity per IP, total luminosity per year (two IPs), luminosity target, and run time for each FCC-ee working point.

Working Point	Luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Tot. lum./year $[\mathrm{ab}^{-1}$ / year]	Goal $[\mathrm{ab}^{-1}]$	Run Time [years]
Z (first two years)	100	24	150	4
Z (other years)	200	48		
W	25	6	10	2
H	7.0	1.7	5	3
RF reconfiguration				1
$t\bar{t}$ 350 GeV (first year)	0.8	0.19	0.2	1
$t\bar{t}$ 365 GeV	1.5	0.34	1.5	4