Beam-Beam Simulations for LHC and LHC Crab Cavities

Stefan Paret and Ji Qiang

Outline

- Simulation code: BeamBeam3D
- Crab cavity and noise
- Beam-beam effects
  - Tune scans
  - Collisions with offset
- Summary
- Outlook

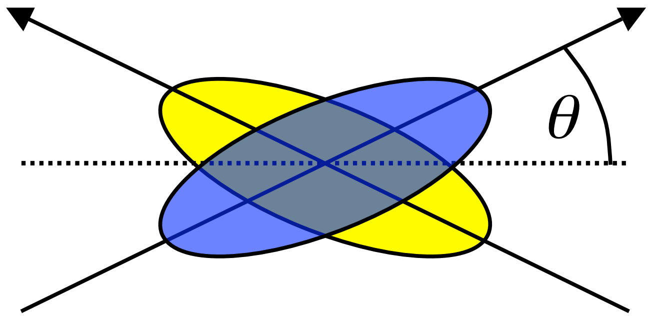
Simulation Code: BeamBeam3D

- Strong-strong beam-beam interaction
- Integrated shifted Green function method
- Particle based parallel domain decomposition
- First order beam transport, chromaticity included
- Supports:
  - Multiple slices
  - Crab cavities
  - Offset at IP
  - Multiple bunches and IPs
  - Noise

Beam Dynamics with Crab Cavities

Crossing Angle and Luminosity

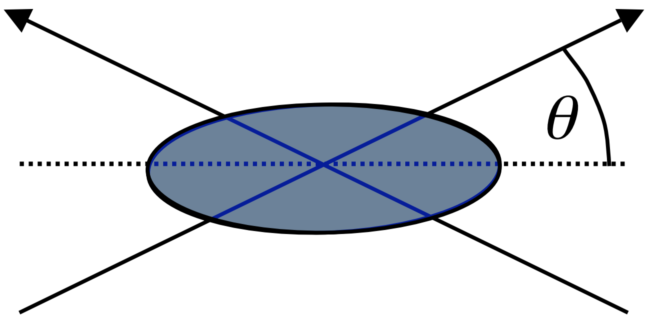
Crossing angle avoids parasitic interactions but causes luminosity loss



$$L = \frac{L_0}{\sqrt{1+\Theta^2}}$$

$$\Theta = \frac{\tan\theta\,\sigma_z}{\sigma_x}$$

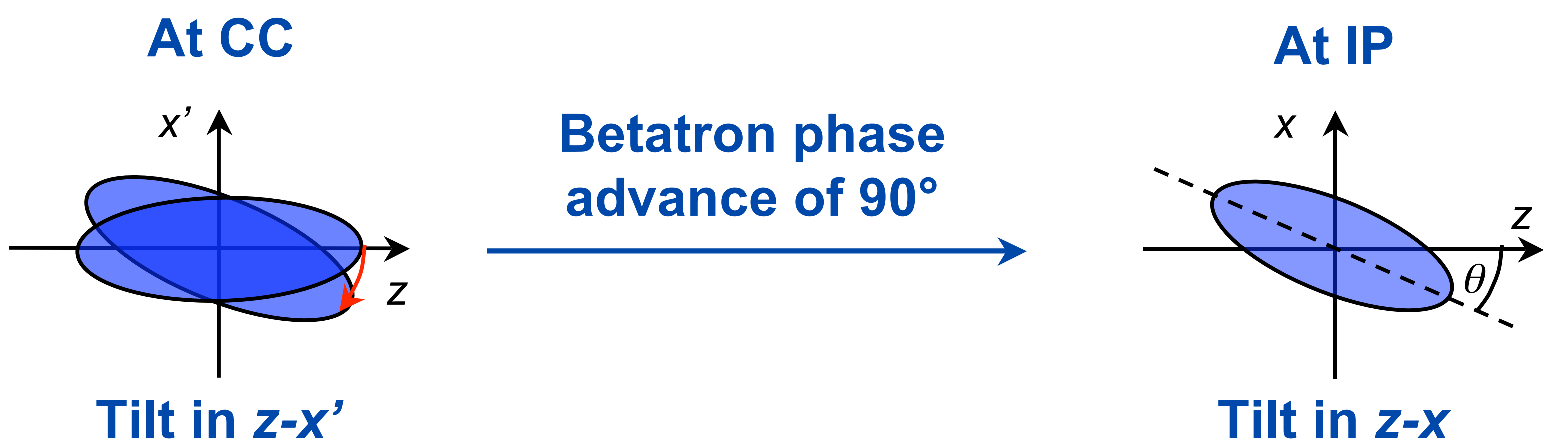
L can be recovered tilting the bunches by θ



Crab Cavity (CC) Scheme

- Apply *z*-dependent transverse kick

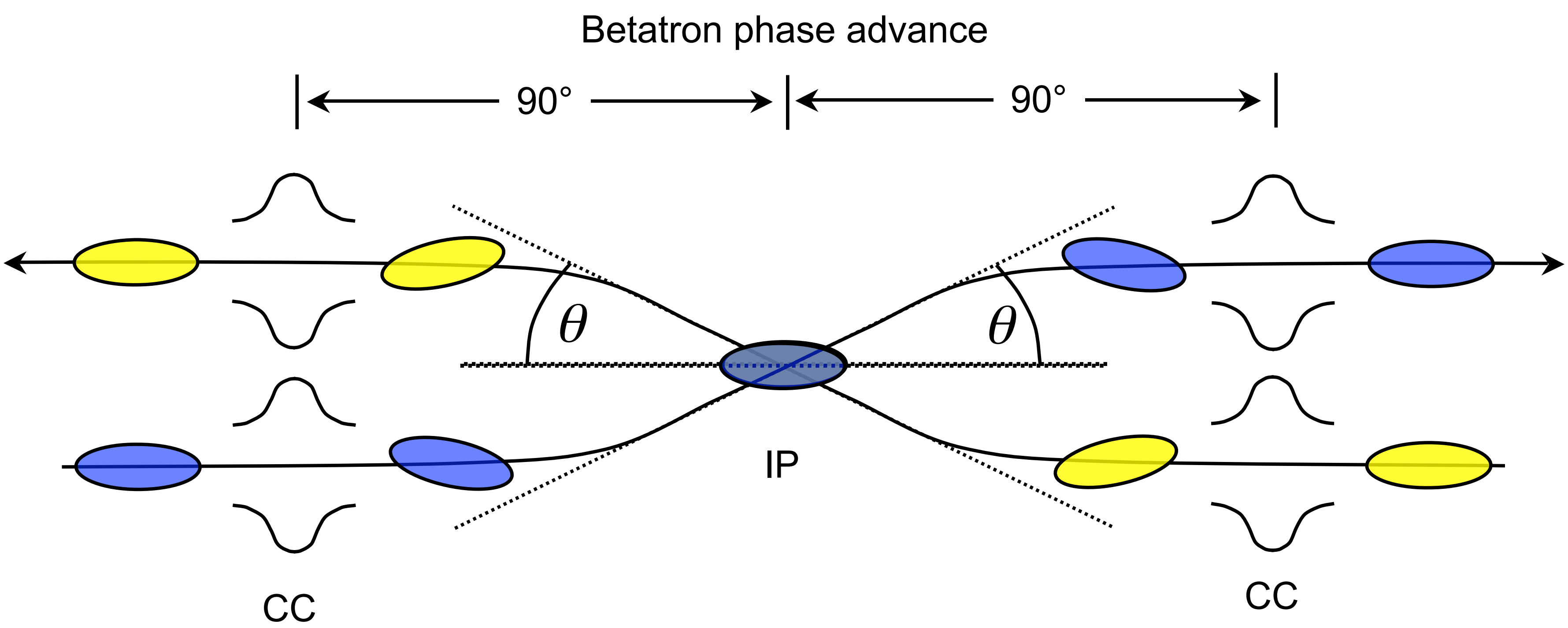
$$\Delta x'_{crab} = -\frac{c\tan\theta}{2\pi f_{crab}\sqrt{\beta_{crab}\beta^*}}\sin\left(\frac{2\pi f_{crab} z}{c}\right)$$



- Similar kick to δ*p*

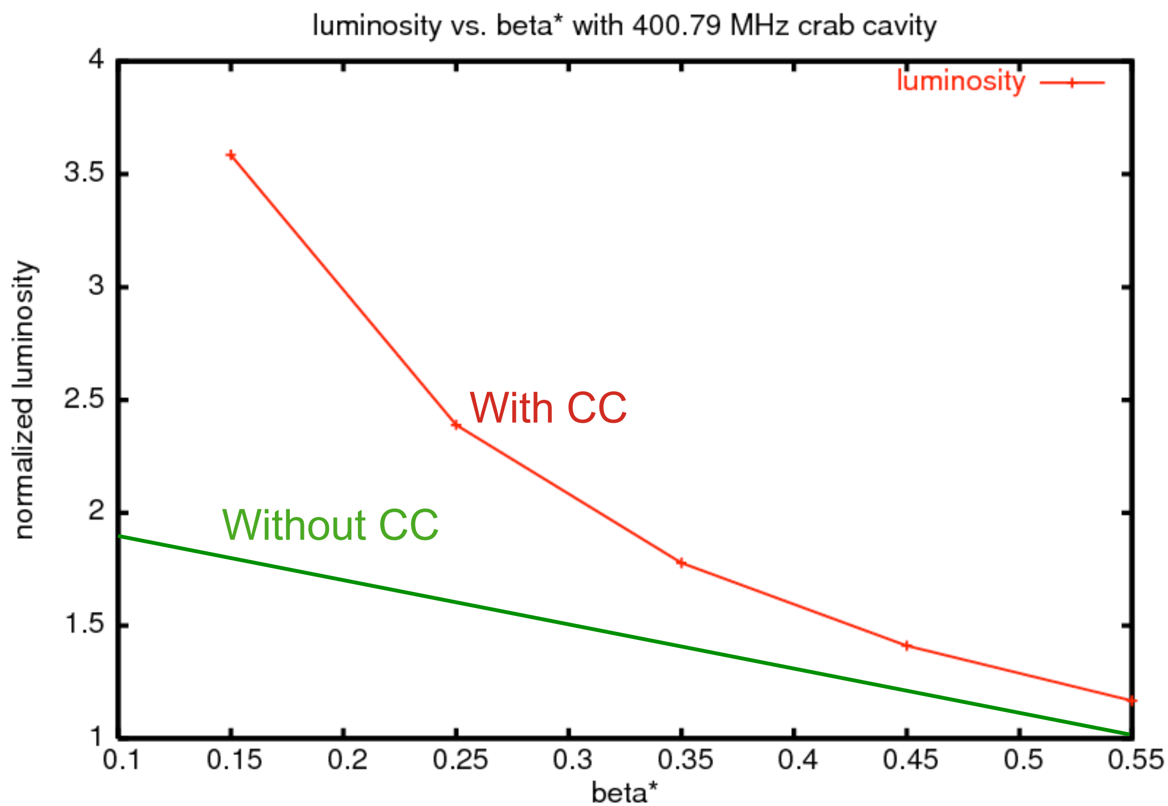
Local Crab Cavity Scheme

- **Second CC behind IP neutralizes kick**



Luminosity with Crab Cavities

- **Ideal CC promises luminosity gain for small β***



Courtesy J. Qiang

Crab Cavity Status

- **Design still ongoing [1]**
- **Beam dynamics with CC subject to investigation**
- **CC are an essential element of HL-LHC [2]**
- **Topic here: Impact of noise**

[1] R. Calaga's presentation

[2] Summary of 4th LCH Crab Cavity Workshop "LHC-CC10", Dec. 2010

Crab Cavities and Noise

- Phase jitter in CC causes random offset at IP
  $\Rightarrow$ emittance growth and luminosity decline
- Noise spectrum not known
  different model assumptions:
  - Single peak at certain frequency
  - Diffusive (Ornstein-Uhlenbeck process)
  - …
- Suggestion from W. Herr: consider all reasonable models

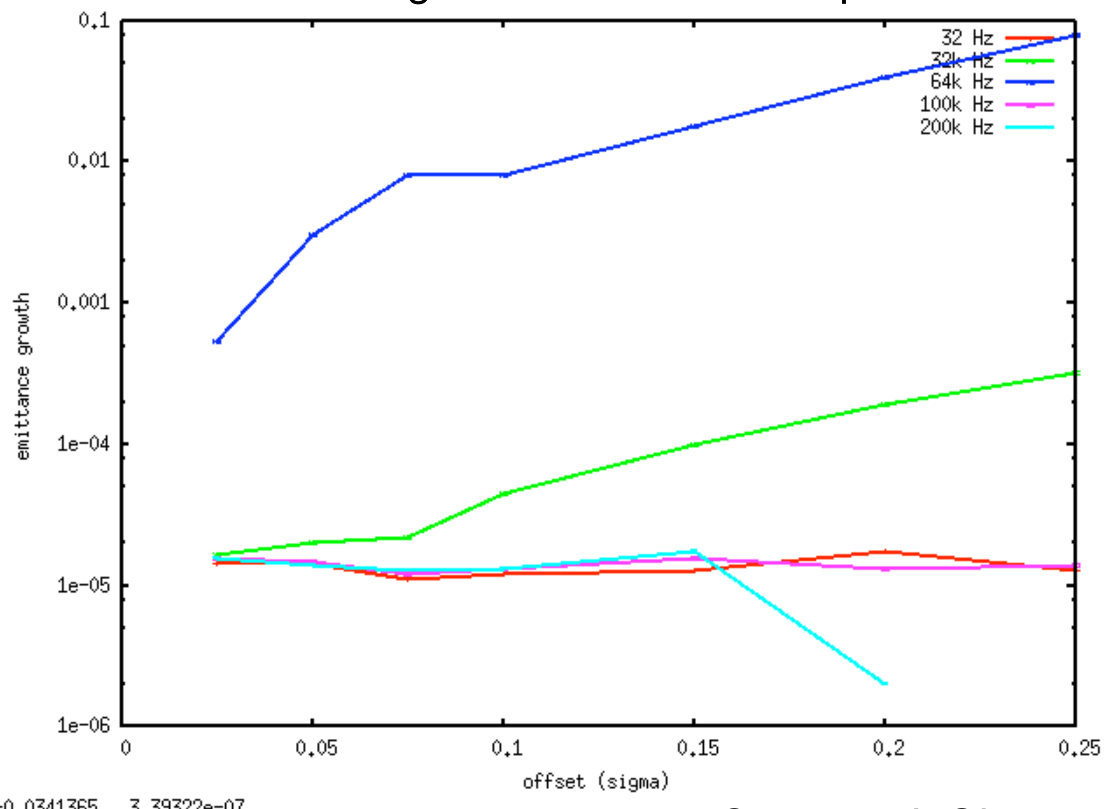
Beam Parameters

N	1.15×10^{11}
ε_n	3.75 μm
E	7 TeV
β^*	0.5 m
Bunch length	7 cm
$\delta p/p$	1.11×10^{-4}
#IPs	1

Noise at Single Frequency

- **Studied at KEK, CERN and LBNL [1]**
- **Numerical study presented at 14th LARP CM (J. Qiang)**
- **Conclusion: Dangerous if coincident with tune resonance**

Emittance growth for different frequencies



[1] R. Calaga et al., PAC07

Courtesy J. Qiang

Diffusive noise

- **Statistical model of head on collisions with noise yields [1]**

$$x_{n+1} = \left(1 - \frac{1}{\tau}\right) x_n + \sqrt{\frac{2}{\tau}}\sigma_{noi}\zeta_{n+1}$$

Correlation time (τ)

Standard deviation of noise (σ_{noi})

Random number (ζ_{n+1})

- **Numerically studies indicate emittance growth [2,3]**

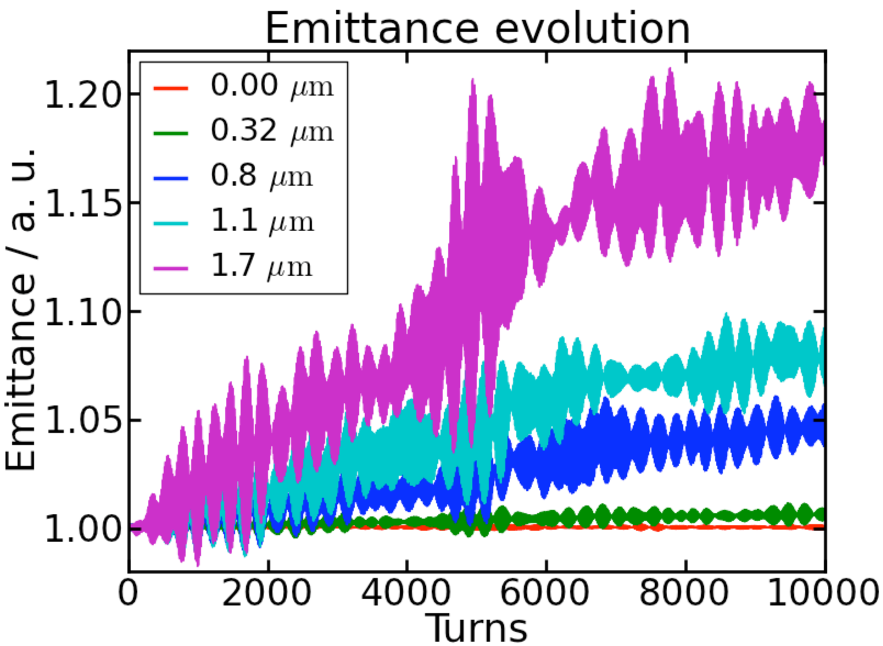
[1] M. P. Zorzano et al., EPAC2000

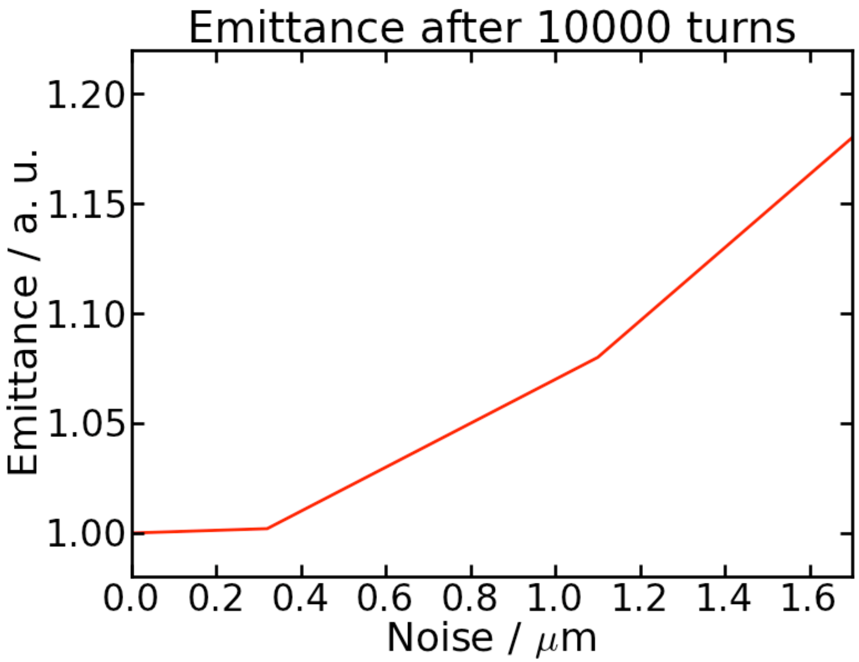
[2] K. Ohmi, 1st CARE-HHH-APD Workshop, 2004

[3] J. Qiang, PAC09

Results for Diffusive Noise I

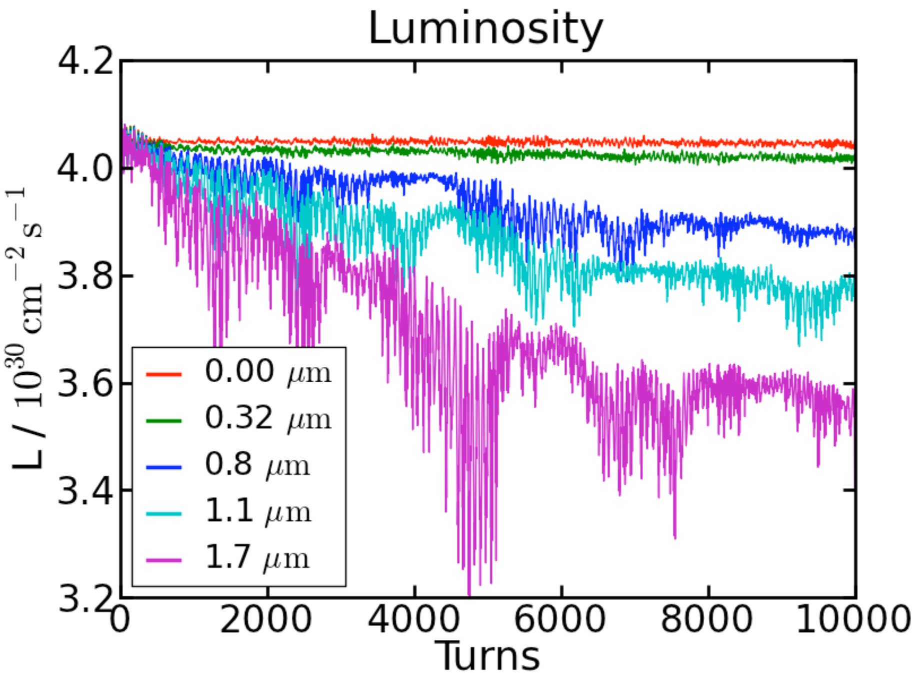
- **Goal: Benchmarking of BeamBeam3D with Ohmi's code**

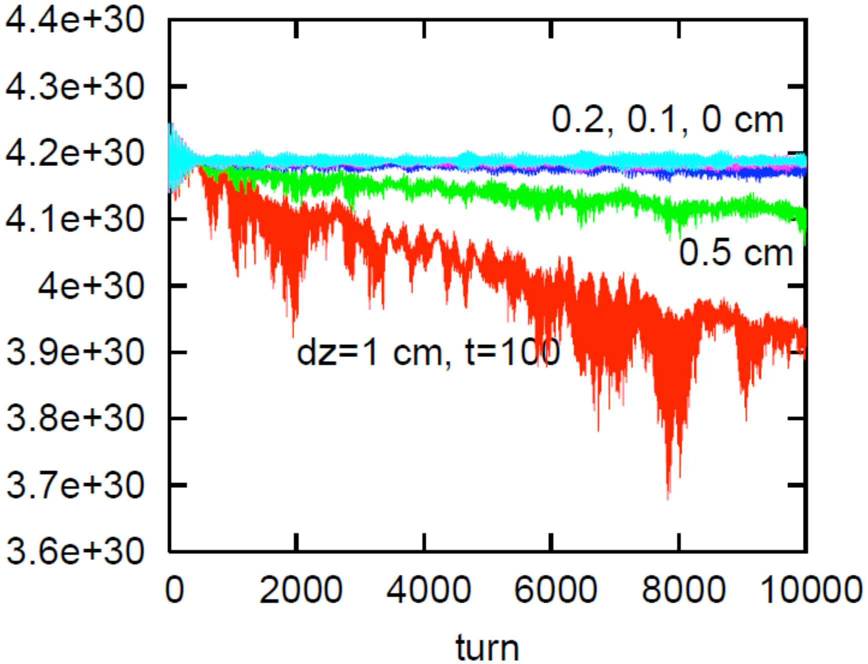




Results for Diffusive Noise II

- **Results look similar, however details of settings in Ohmi's computations need to be inquired**





Right figure: courtesy K. Ohmi [1]

[1] K. Ohmi, 1st CARE-HHH-APD Workshop, CERN, 2004

Beam-Beam Effects (BBEs)

Beam dynamics with collisions

- Opposite beam like nonlinear lens

  Defocusing for equal charges

- Particle dependent tune shift ⇒ tune spread

- Maximal tune shift = beam-beam parameter

  convenient measure for BBE strength

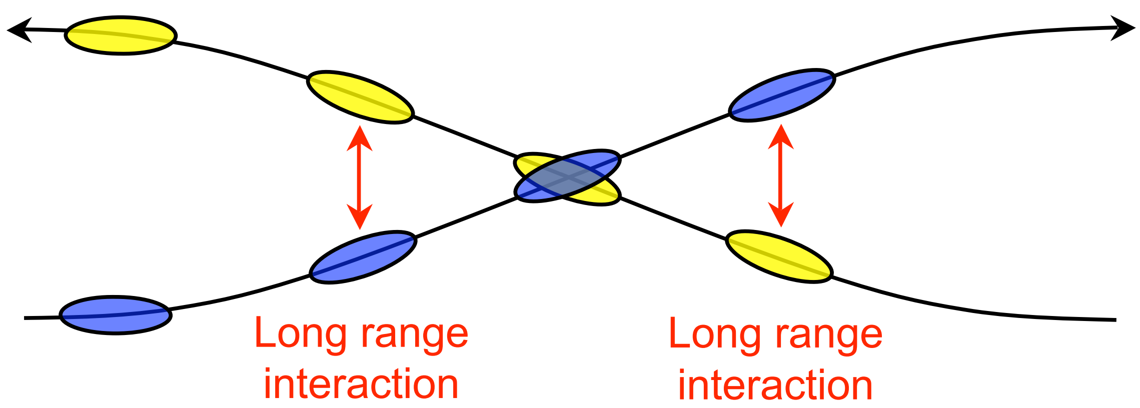
$$\xi_y = \frac{N r_p \beta_y^*}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)}$$

- Impact on emittance, orbit, lifetime, …

- Feedback system can mitigates BBE

Long Range Effects (LRE)

- Close to IPs bunches may interact with by-passing bunches of other beam
  $\Rightarrow$ asymmetric, non-linear force



- Up to 120 LREs per turn

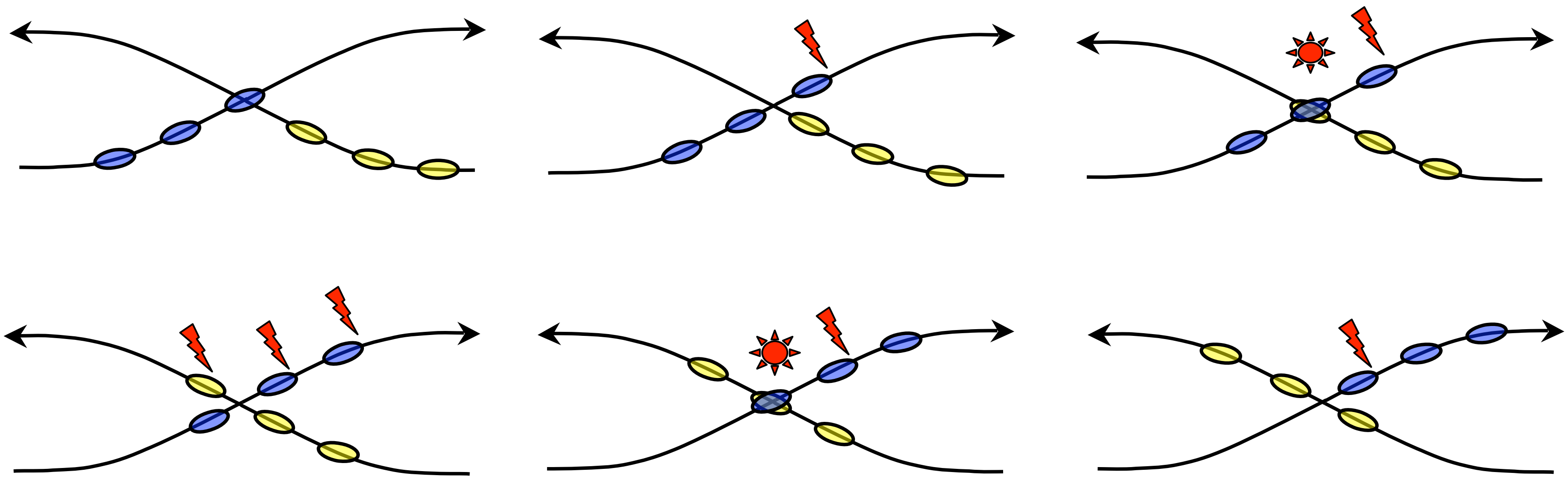
Pacman Effect

- **LHC features**
  - **Bunches separated by gaps of varying length**
  - **Asymmetric IP alignment**

⇒ Different number of collisions and LRE for different bunches

Illustration follows…

Illustration of Pacman Effect



Bunch	Collisions	LRE
Blue 1	0	3
Blue 2	1	2
Blue 3	1	2

Pacman effect

- **LHC features**
  - Trains of bunches with gaps of varying length
  - Asymmetric IP alignment

⇒ **Different number of collisions and LRE for different bunches**

⇒ **Individual tune spreads, orbit deformations,… Major concern for performance**

- **Simulation requires many bunches**
- **Numerically studied [1] but far from all-embracing**

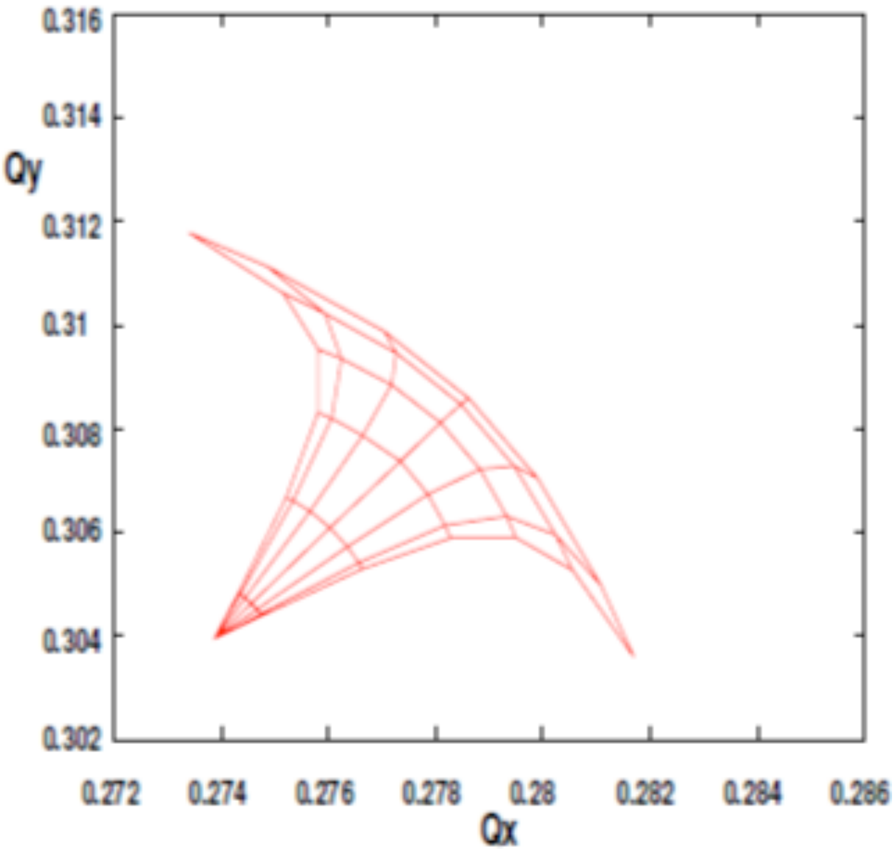
[1] T. Pieloni, PhD Thesis, EPF Lausanne, 2008

Emittance Growth and Tune

- **LRE modify tune footprint [1]**
- **Emittance growth due to noise depends on tune [2]**

⇒ Tune should be optimized for operation with BBE

Tune footprint for collision and LRE



Courtesy W. Herr [2]

[1] W. Herr, Proc. of CAS 2003

[2] J. Qiang, 14th LARP CM

Operational Scenarios

Recommendations/proposal IP1/5

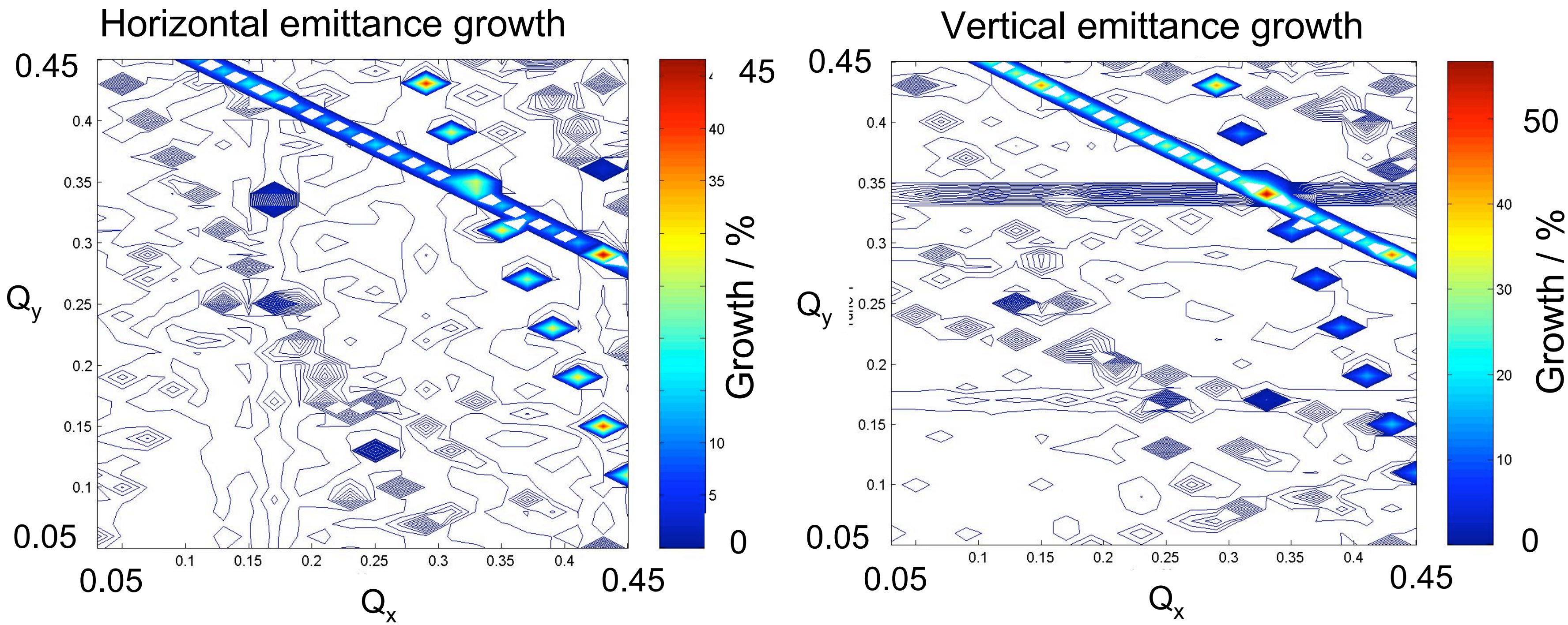
ϵ_n Energy	β^* (3.5 TeV)	β^* (4.0 TeV)	α (3.5 TeV)	α (4.0 TeV)
1.5 μm	1.4 m	1.4 m	$\pm$ 120 μrad	$\pm$ 120 μrad
2.0 μm	1.5 m	1.4 m	$\pm$ 120 μrad	$\pm$ 120 μrad
2.5 μm	1.6 m	1.5 m	$\pm$ 120 μrad	$\pm$ 120 μrad
3.75 μm	1.8 m	1.6 m	$\pm$ 140 μrad	$\pm$ 140 μrad

- Optimized working point would help (tune scan !)

Courtesy W. Herr [1]

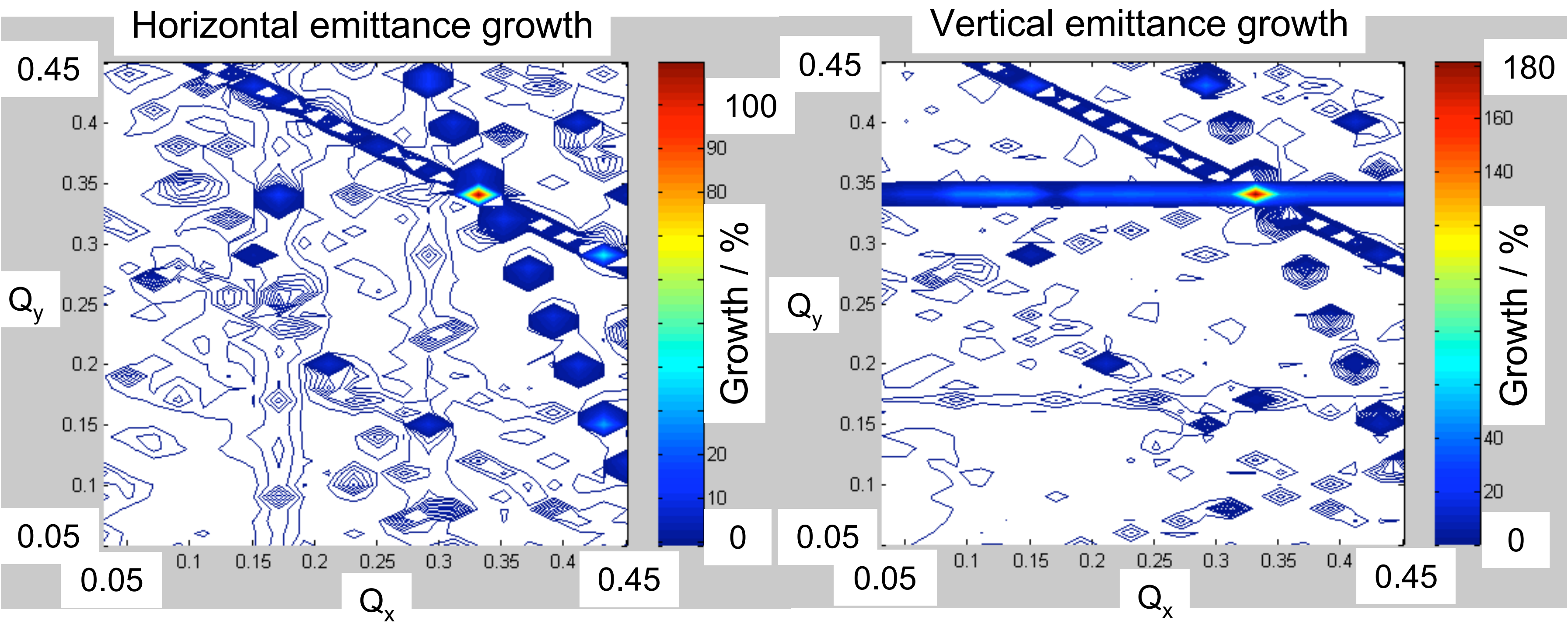
[1] W. Herr, Chamonix 2011 LHC Performance Workshop

Emittance Growth - Scenario 4



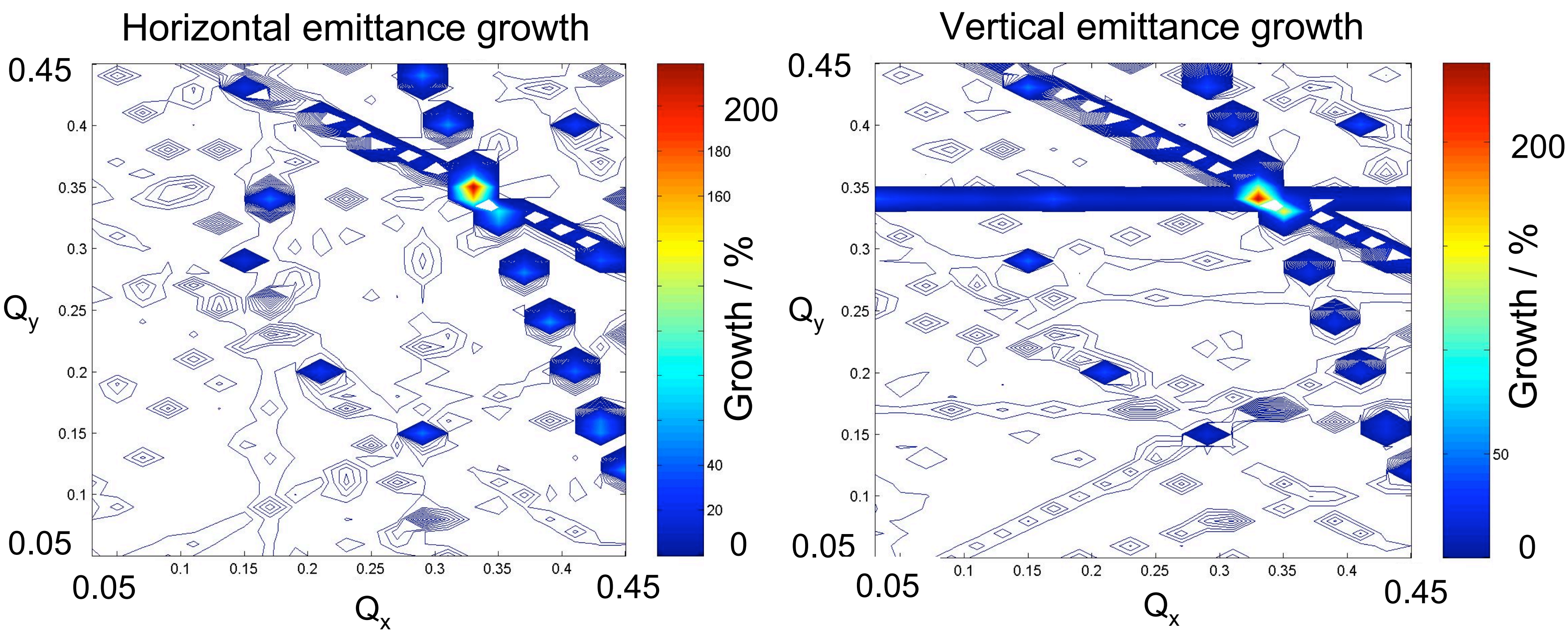
Courtesy J. Qiang

Emittance Growth - Scenario 3



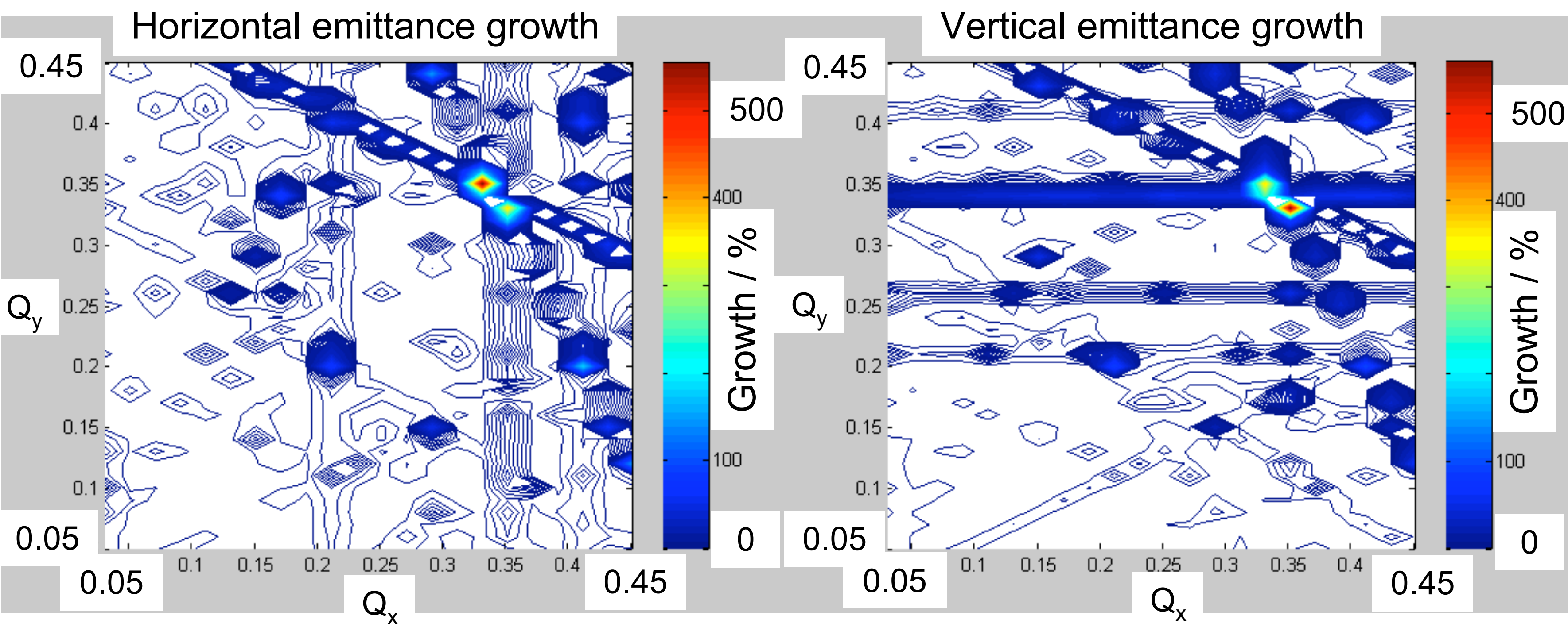
Courtesy J. Qiang

Emittance Growth - Scenario 2



Courtesy J. Qiang

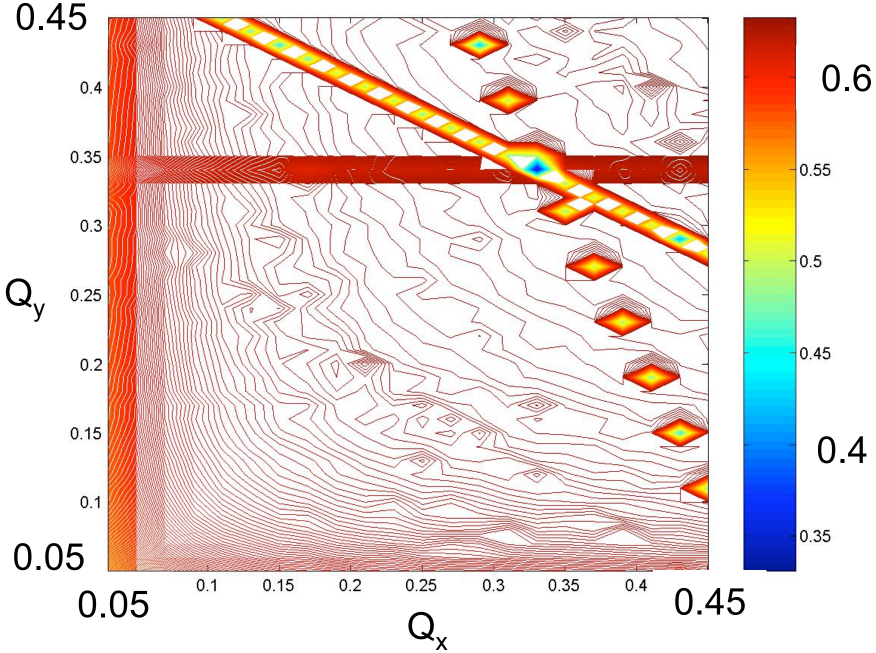
Emittance Growth - Scenario 1



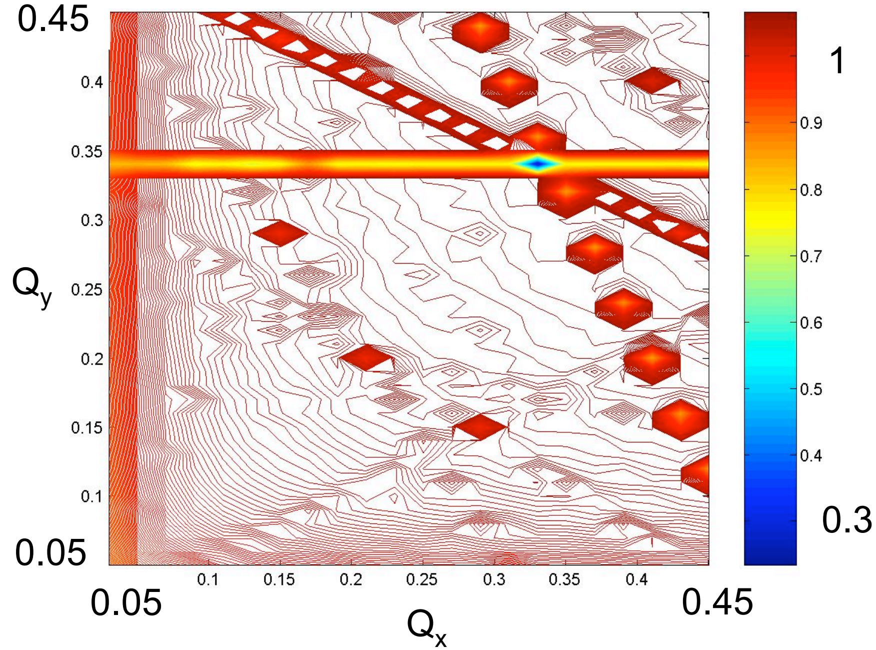
Courtesy J. Qiang

Luminosity - Scenarios 4 & 3

Scenario 4

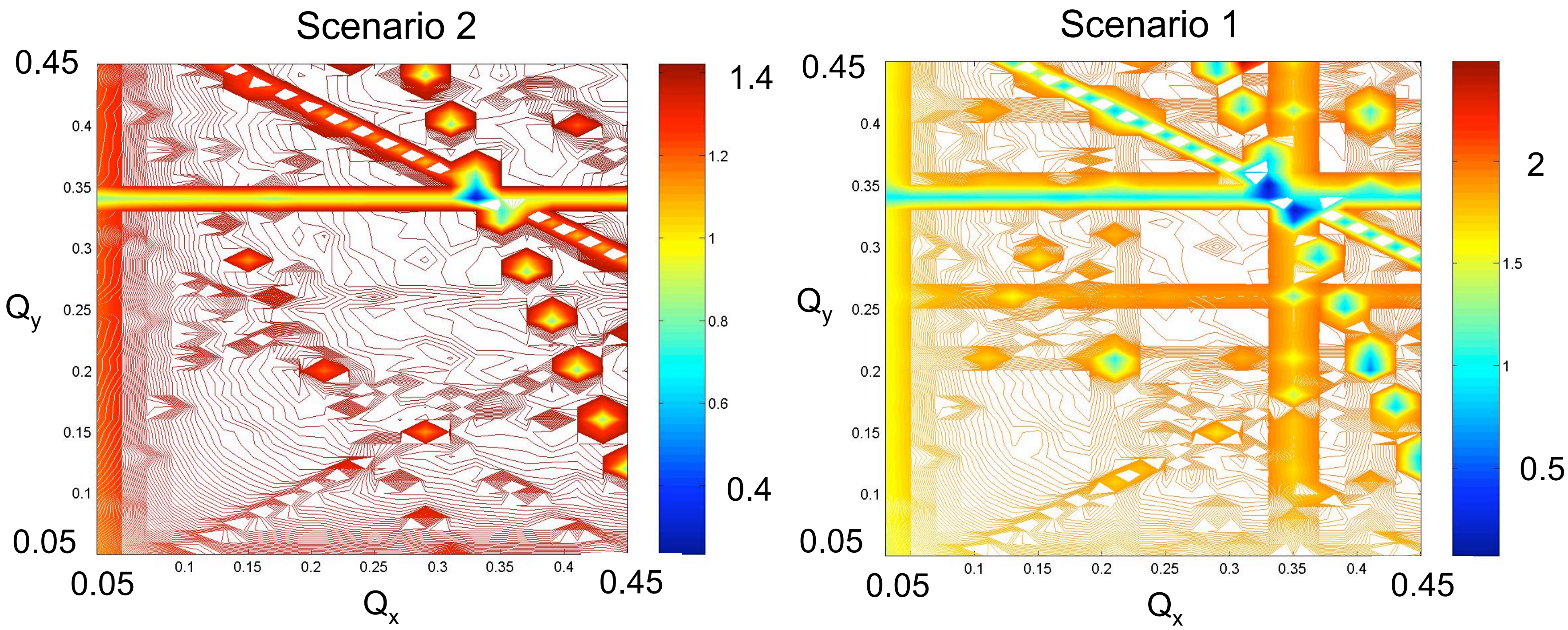


Scenario 3



Courtesy J. Qiang

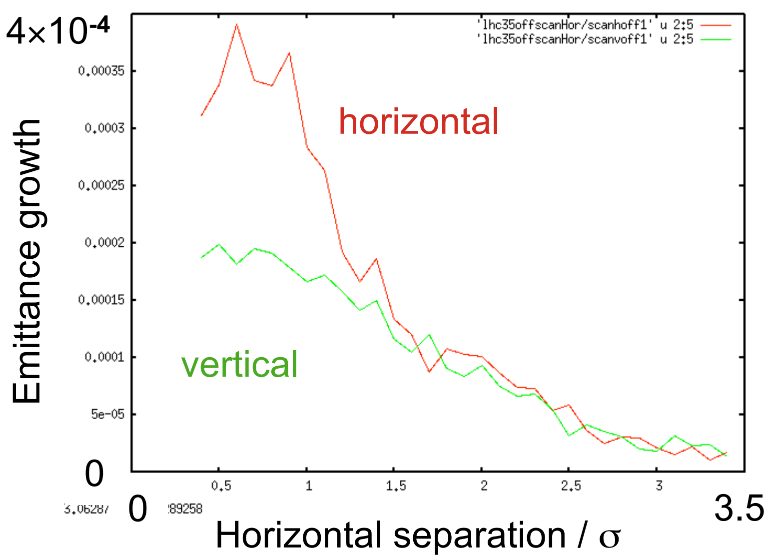
Luminosity - Scenarios 2 & 1

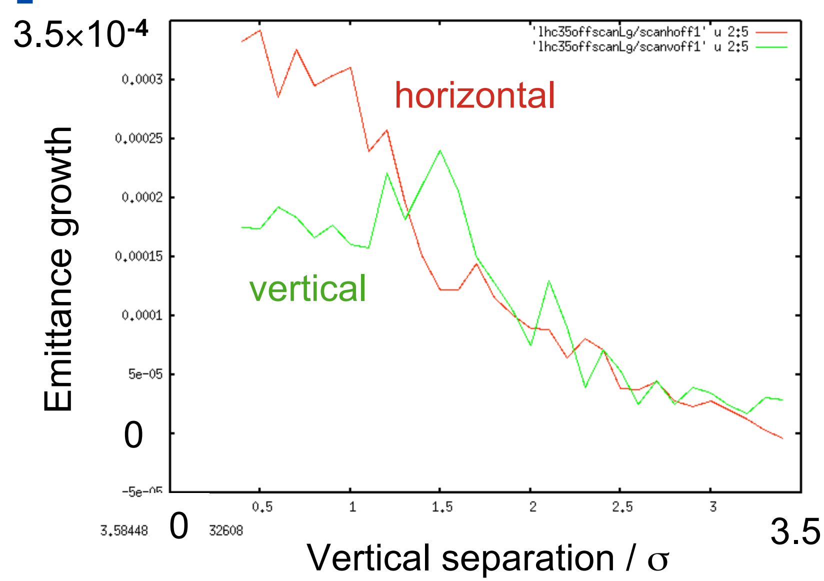


Courtesy J. Qiang

Static Offset *(in progress)*

- **Collision with offset breaks symmetry of beam-beam force**
- **Induces emittance growth [1]**





Courtesy J. Qiang

- **Dependence on beam parameters not clear**

[1] T. Pieloni, PhD Thesis, EPF Lausanne, 2008

Summary

- **Simulations of CC with noise**
- **Tune scans with BBE**
- **BBE with offsets**

We appreciate the cooperation with CERN

Mainly R. Calaga, W. Herr and T. Pieloni

Outlook

- Continue CC simulation with noise
- Study beam-beam limit with CC
- Continue offset studies
- Include LRE
- Provide input for experiments in LHC
  (e. g. tune scans)