Beam-beam effects in space charge dominated ion beams

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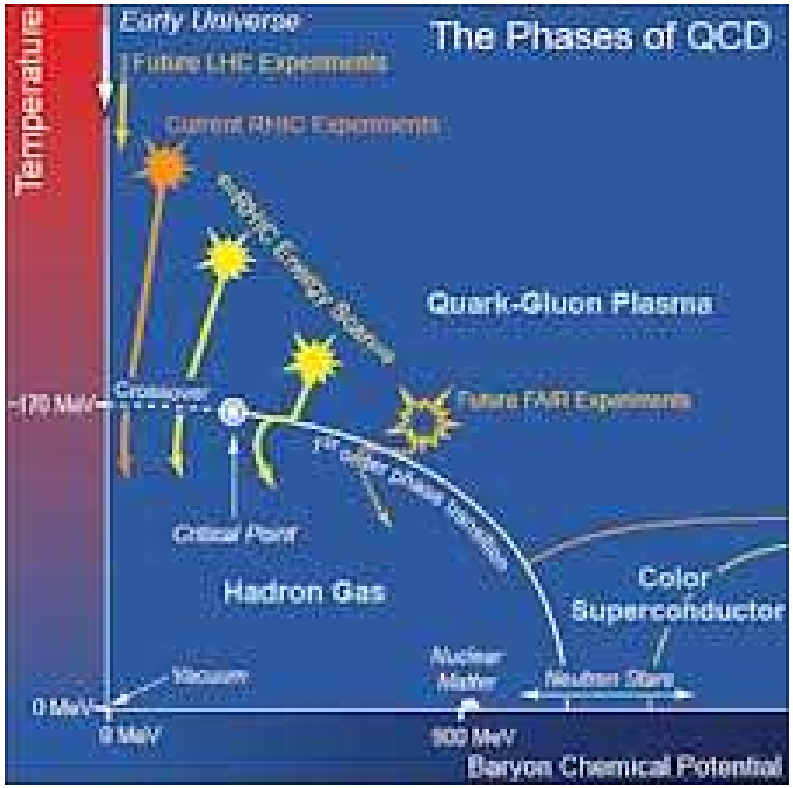
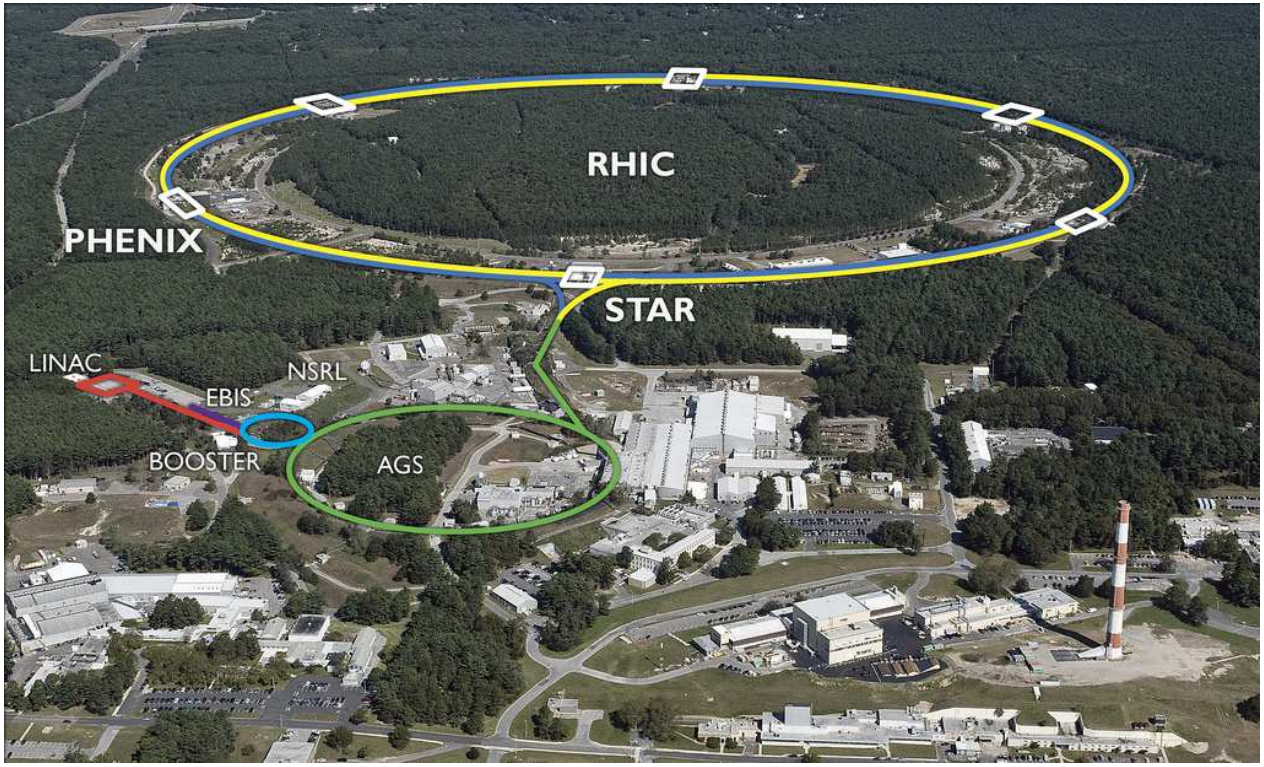
The QCD Phase Diagram



Goal:

Search for the QCD critical point, believed to be somewhere between $\sqrt{s} = 5\,\mathrm{GeV/n}$ and $30\,\mathrm{GeV/n}$

The Relativistic Heavy Ion Collider



Circumference: $C = 3833.845\,\mathrm{m}$

Nominal Au beam energy range: $E = 10\,\mathrm{GeV/n}{-}100\,\mathrm{GeV/n}$

Energy range for critical point search is (well) below design energies

Known Challenges at Low Energy

- Transverse beam size
- Intrabeam scattering
- Magnet nonlinearities
- Space charge

Experimental Observations

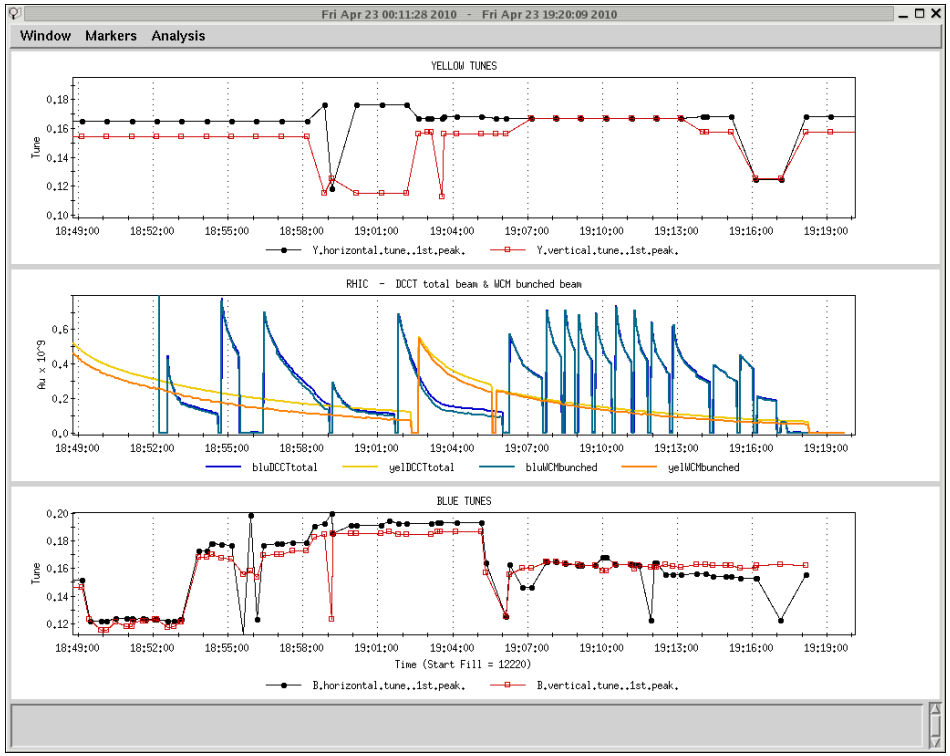
Space Charge Tune Shifts, Beam-Beam Parameters, and Lifetime

E [GeV/n]	ΔQ_{sc}	$\xi_{\mathrm{beam-beam}}$	τ [sec]
9.8	0.03	0	2000
9.8	0.03	0.002	600
5.75	0.05	0	1600
5.75	0.05	0.0015	400
5.75	0.09	0	700
5.75	0.09	0.0027	260
3.85	0.11	0	70
3.85	0.08	0.003	70

Typical beam-beam parameter is more than factor 10 smaller than space charge tune shift

Lifetimes drop by factor 3-4 when beam-beam collisions are added

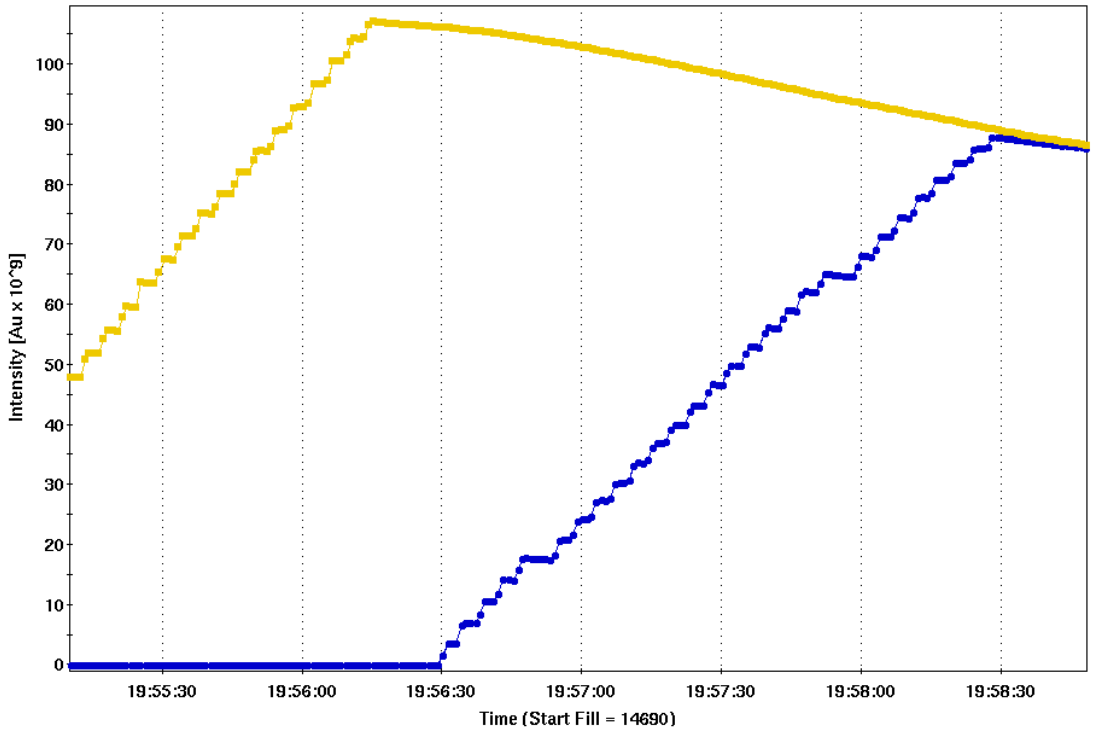
Tune Scan in Blue Ring



Best performance for (.17/.16) instead of the regular RHIC working point of (.23/.22)

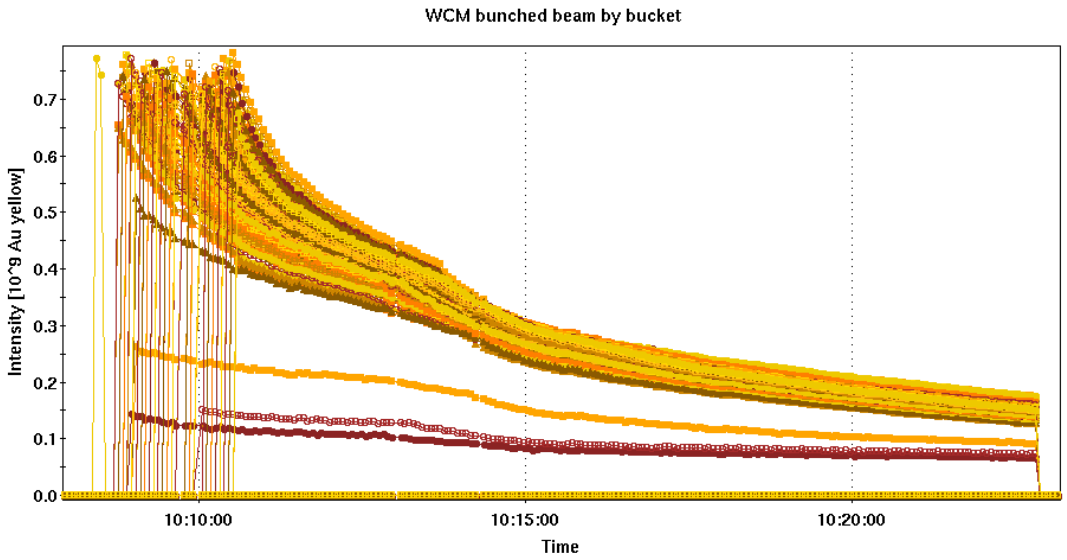
Tunes finally settled at (.13/.12) during the course of the run

Beam intensities at the start of a 5.75 GeV store



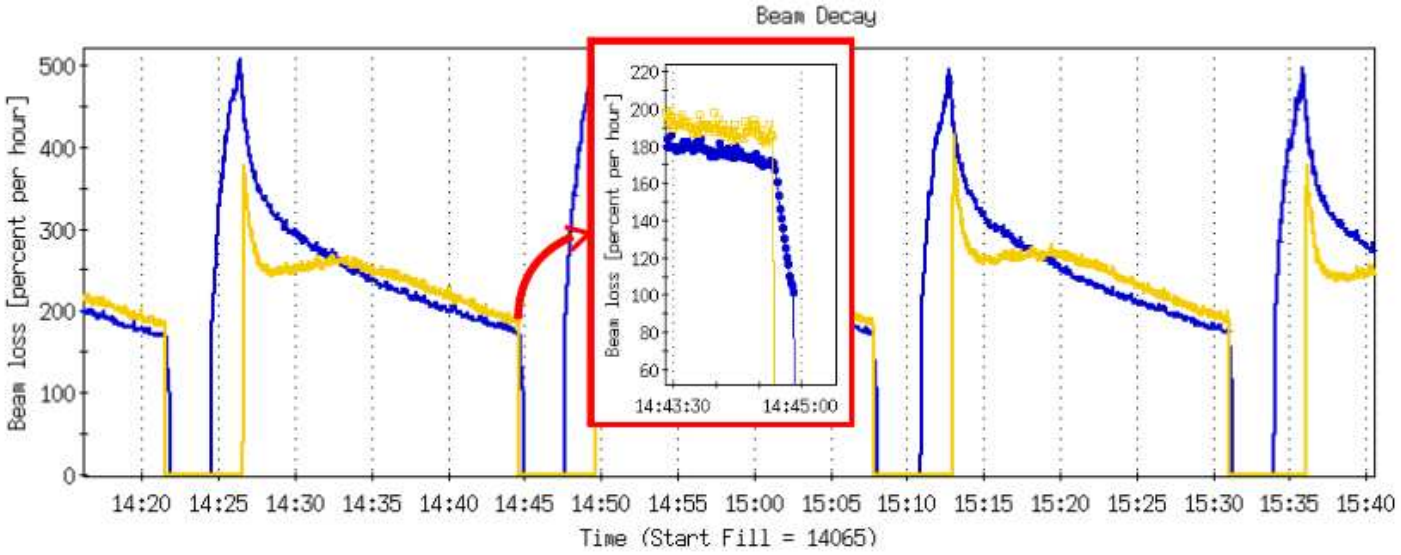
Yellow lifetime deteriorates as Blue is filled (beams are always in collision)

Beam intensities at 3.85 GeV when beams are brought into collision



Yellow lifetime deteriorates when beams are brought into collision

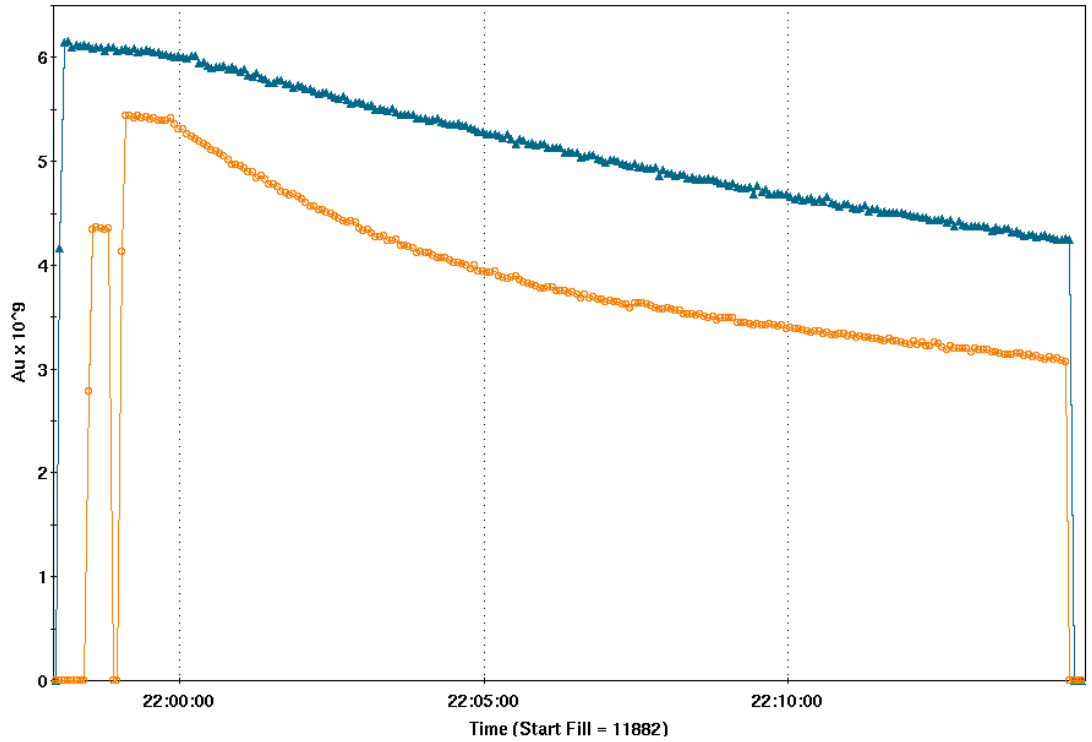
Beam decay rate at 5.75 GeV



Blue beam decay improves dramatically as soon as Yellow is dumped at the end of store

Though $\xi_{\mathrm{beam-beam}} << \Delta Q_{\mathrm{sc}}$, beam-beam has a strong effect on beam lifetime

Intensities at 9.8 GeV, regular working point

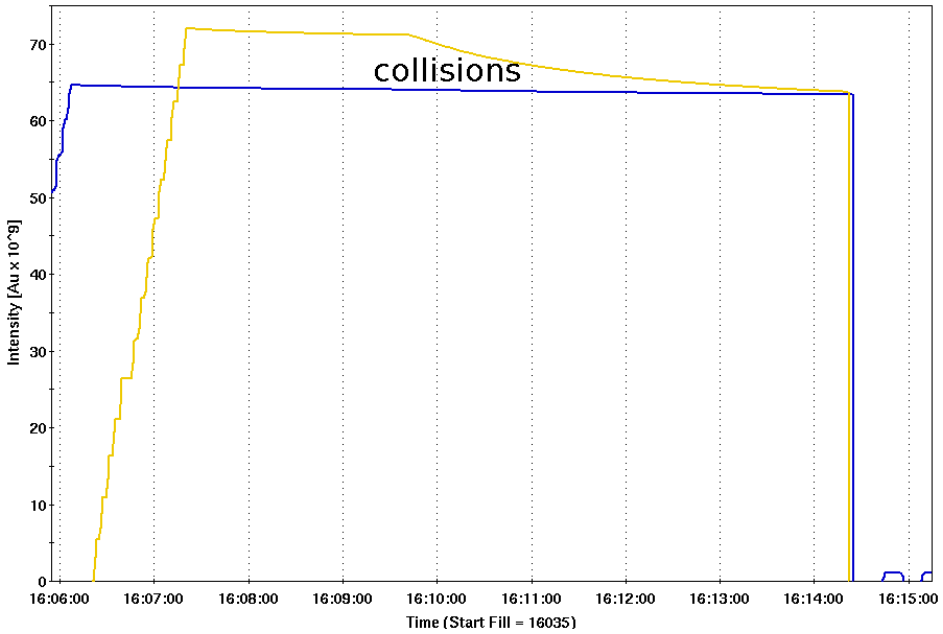


Working point: (.23/.22)

Strong beam-beam effect in both rings with $\Delta Q_{\mathrm{SC}} = 0.03$, $\xi_{\mathrm{beam-beam}} = 0.002$

Intensities at near-integer tunes (APEX), E=9.8 GeV

Near the integer, spacing between nonlinear resonances is largest



Working point: (.08/.09) in Yellow, (.08/.07) in Blue
Almost no beam-beam effect in the Blue ring with $\Delta Q_{\mathrm{sc}} = 0.03$, $\xi_{\mathrm{beam-beam}} = 0.002$

Simulations

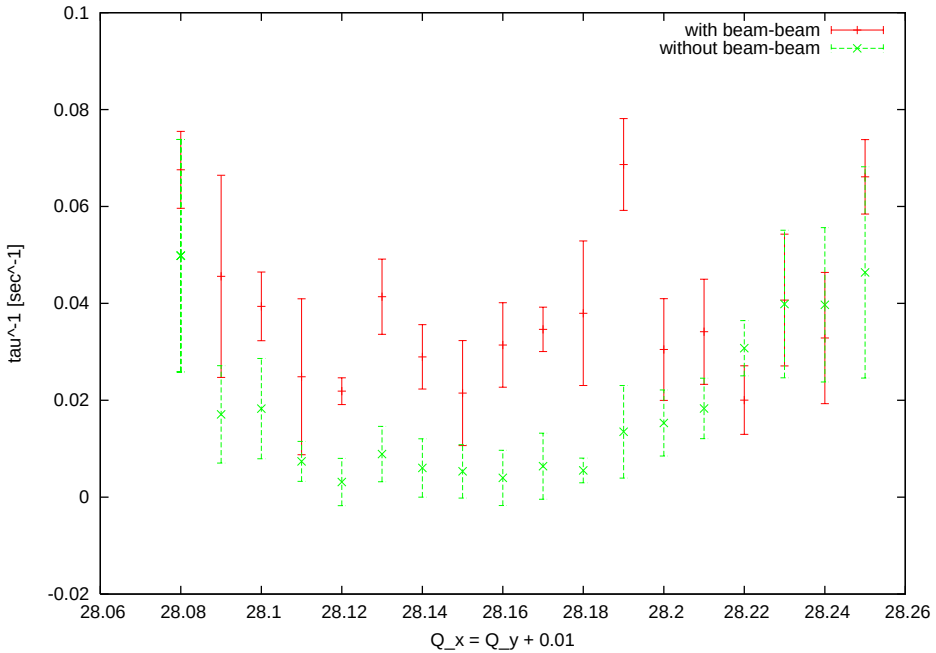
Still in progress...

Simulation Model

- 6-D simulation in RHIC lattice, no nonlinearities beyond sextupoles
- 1000 particles tracked over 20000 turns
- Space charge kicks are applied at each quadrupole
- Assume beam distribution is unchanged during simulation time ("weak-strong" space charge model); dynamic β due to space charge and beam-beam taken into account
- 2 Interaction points, $\Delta Q_{\mathrm{sc}} = 0.06$, $\xi_{\mathrm{beam-beam}} = 0.003$ per IP

Tune Scan

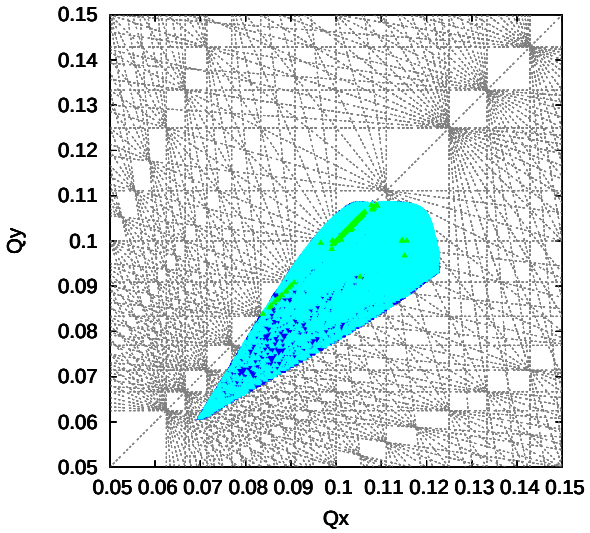
Fractional tune split $\Delta Q = 0.01$

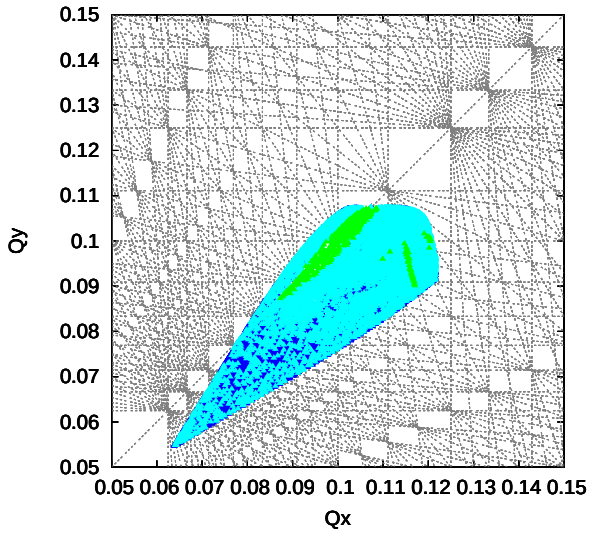


- Significant effect of small beam-beam kick on emittance growth rate
- Without beam-beam, tunes below .20 are clearly better than above, as observed in operations

Frequency Map Analysis

Tune footprints

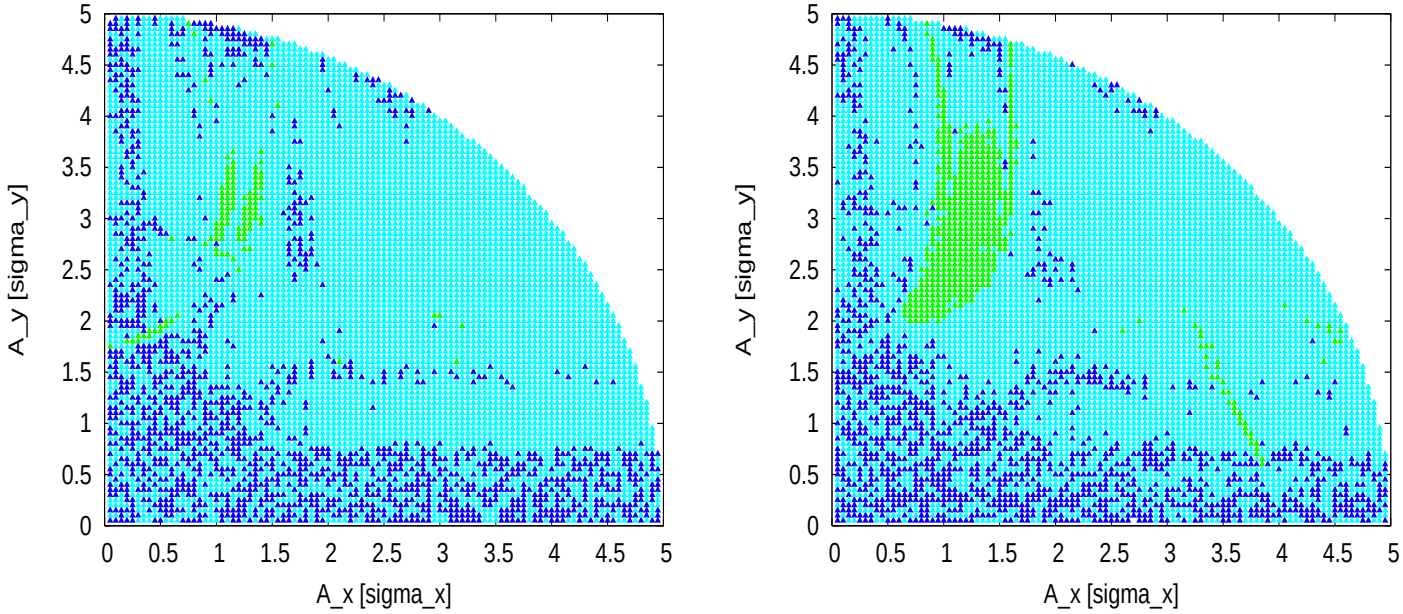




- Beam-beam enhances coupling resonance
- Greater tune split may be beneficial

Frequency Map Analysis

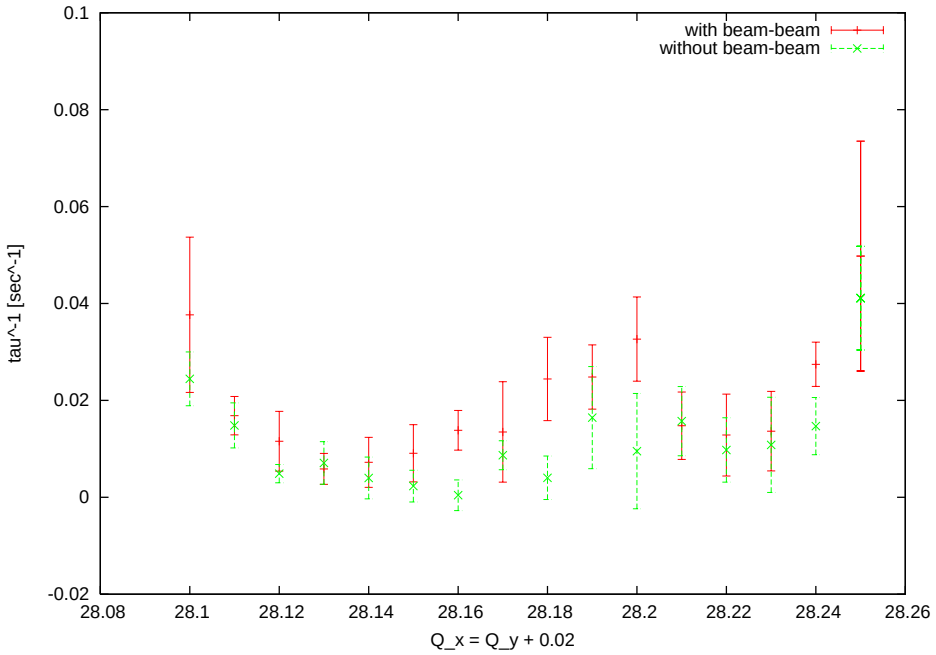
Amplitude space



Beam-beam enhances tune diffusion for $1\sigma_x < A_x < 2\sigma_x$, $2\sigma_y < A_y < 4\sigma_y$

Tune Scan With Increased Tune Split

Enhanced fractional tune split $\Delta Q = 0.02$ to avoid coupling resonance

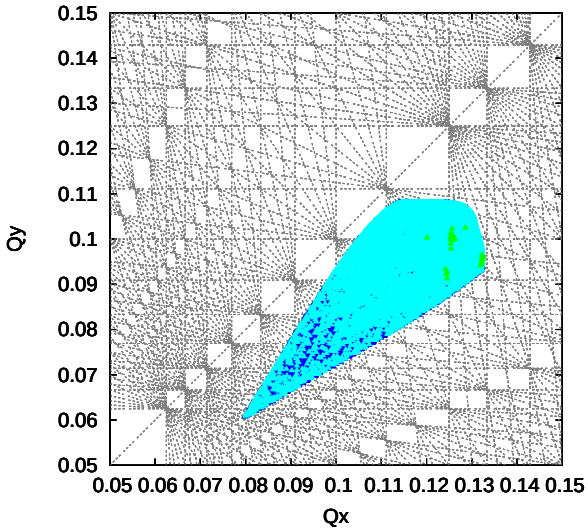


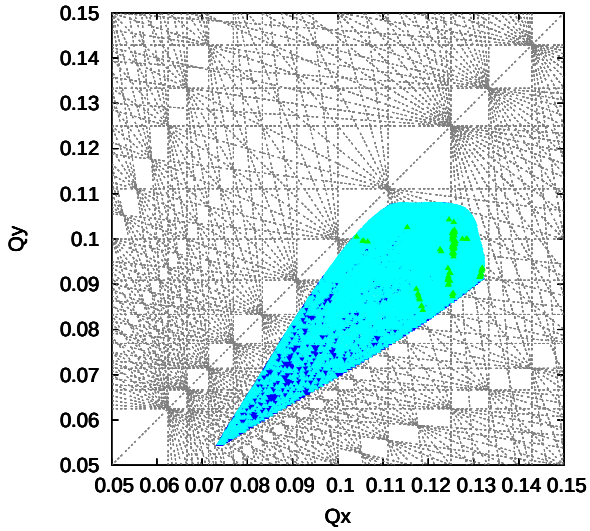
Emittance growth rate due to beam-beam significantly reduced

Needs to be repeated including higher-order multipole errors

Frequency Map Analysis

Tune footprints

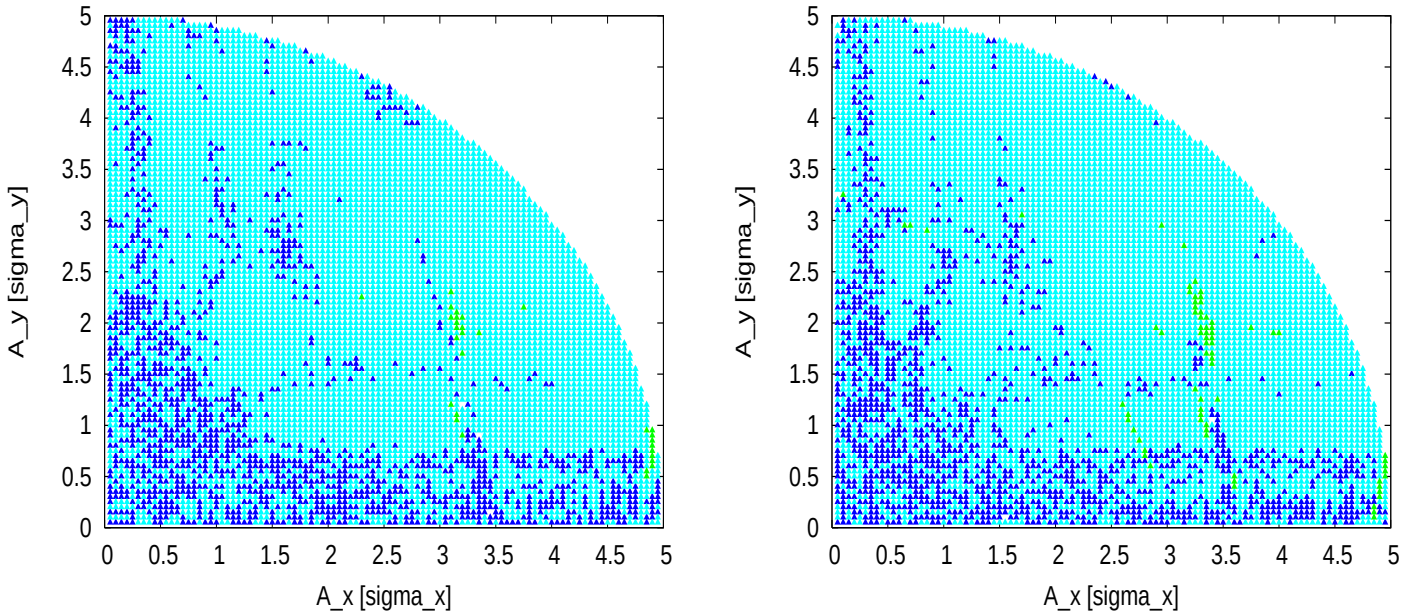




No significant difference caused by beam-beam

Frequency Map Analysis

Amplitude space



No significant difference caused by beam-beam

Summary

- During low energy operations in RHIC, space charge tune shift is very large, up to $\Delta Q_{\mathrm{sc}} = 0.1$
- Though the beam-beam tuneshift is factor 10 smaller, lifetime deteriorates significantly when beams are brought into collision
- This effect may be reduced at near-integer tunes
- Simulations show significant emittance growth due to beam-beam in presence of large space charge, caused by coupling resonance
- Multipole errors need to be included in tracking model to study effect of nonlinear resonances