Luminosity Increase at the Incoherent Beam-Beam Limit with Six Superbunches in RHIC

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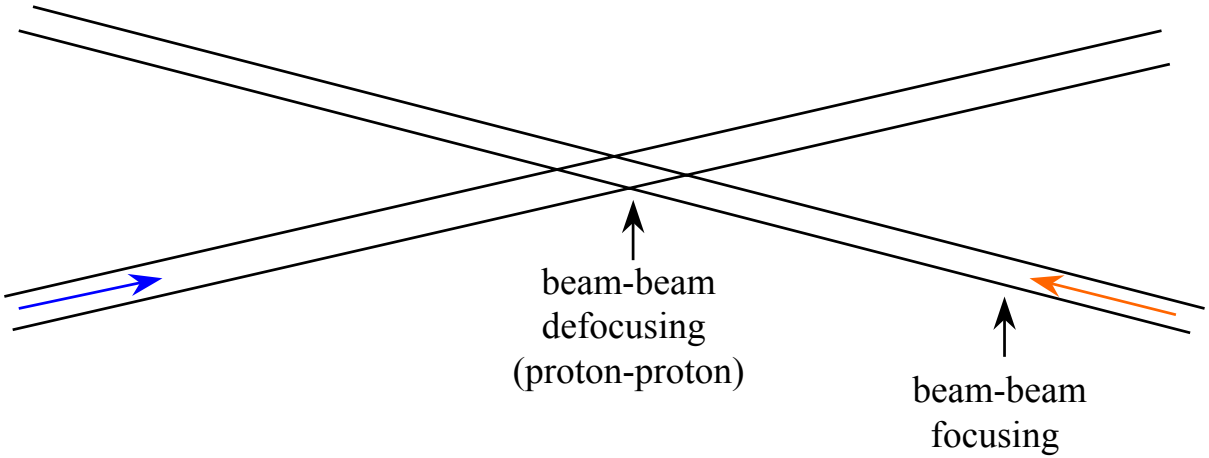
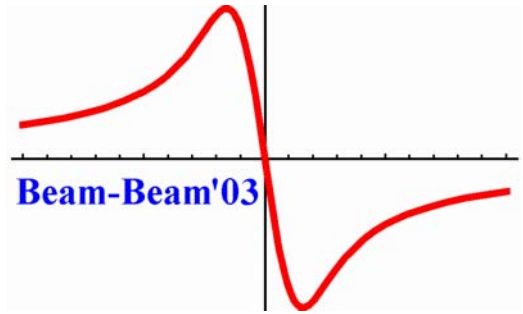
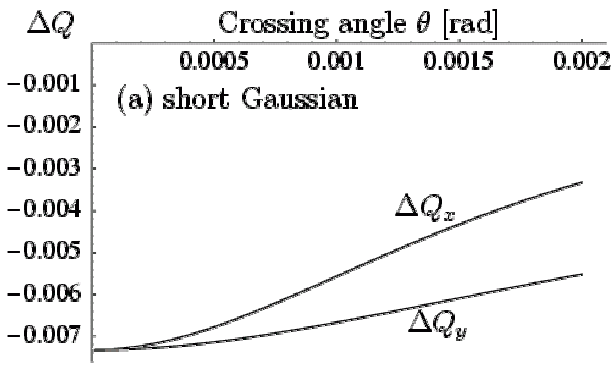
1. Motivation
2. RHIC Parameters
3. Luminosities

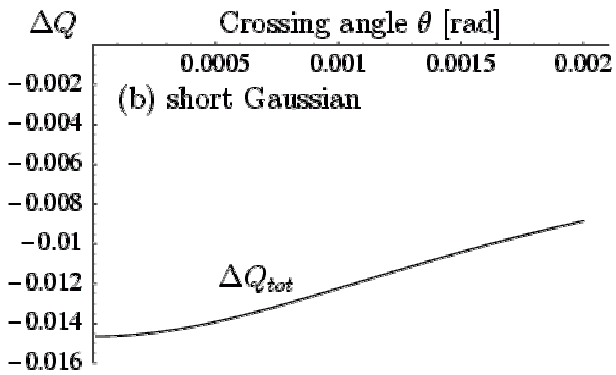




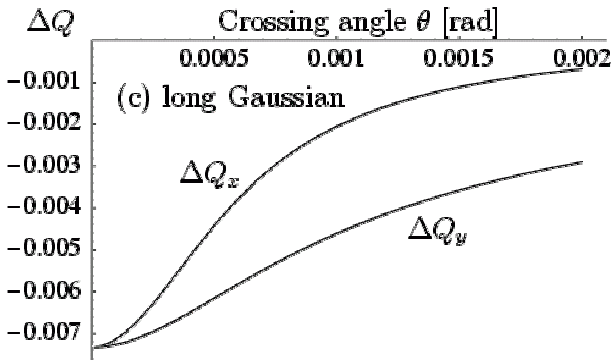
- Partial compensation of beam-beam defocusing in the crossing plane with long bunches and crossing angles
- With 2 crossings in alternating plane same effect in both planes
- Same principle used in LHC for long-range interactions

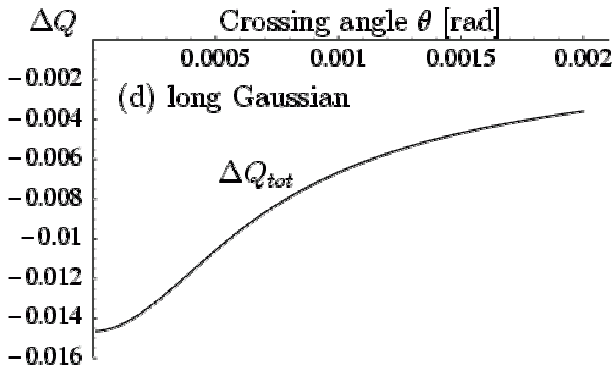
- E. Keil, "Luminosity optimization for storage rings with low-β sections and small crossing angles", Nucl. Instrum. Methods 113, **333** (1973).
  → estimates for unbunched beams, including ISABELLE (gave the RHIC tunnel)
- F. Ruggiero and F. Zimmermann, "Luminosity optimization near the beam-beam limit by increasing the bunch length or crossing angle", Phys. Rev. ST Accel. Beams **5** 061001 (2002).
  → estimates for bunched beams, including a LHC upgrade
- K. Takayama, J. Kishiro, M. Sakuda, Y. Shimosaki, and M. Wake, "Superbunch hadron colliders", Phys. Rev. Lett. Vol. 88 No. 14 (2002).
  → includes proposal of induction cells for barrier cavities and acceleration
  → R&D program for induction cells started in Japan



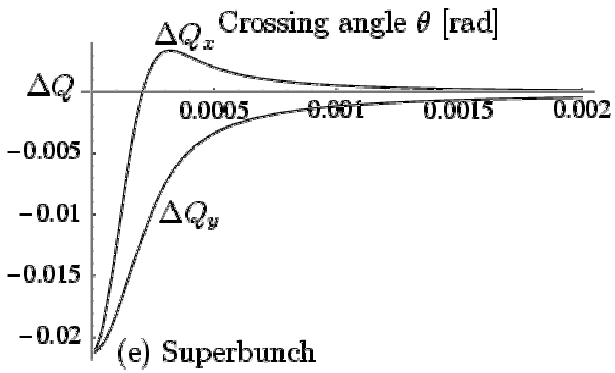


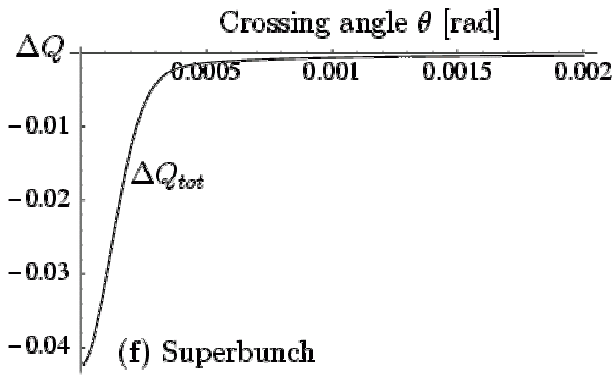
197 MHz rf system
(5ns bunch length)





28 MHz rf system
(36ns bunch length)





Superbunches

- Have barrier buckets at injection to maintain very long bunches (whole circumference with an abort gap)
- Inject into buckets that are then merged with long bunches
- Bunch and accelerate beam with 28 MHz system (up to $4 \cdot 10^{11}$ protons/bunch in 320 buckets, $h = 360$)
- Transfer beam into six superbunches (maintains RHIC symmetry, luminosity can be delivered to any two experiments)
- Adjust superbunch length to run at beam-beam limit

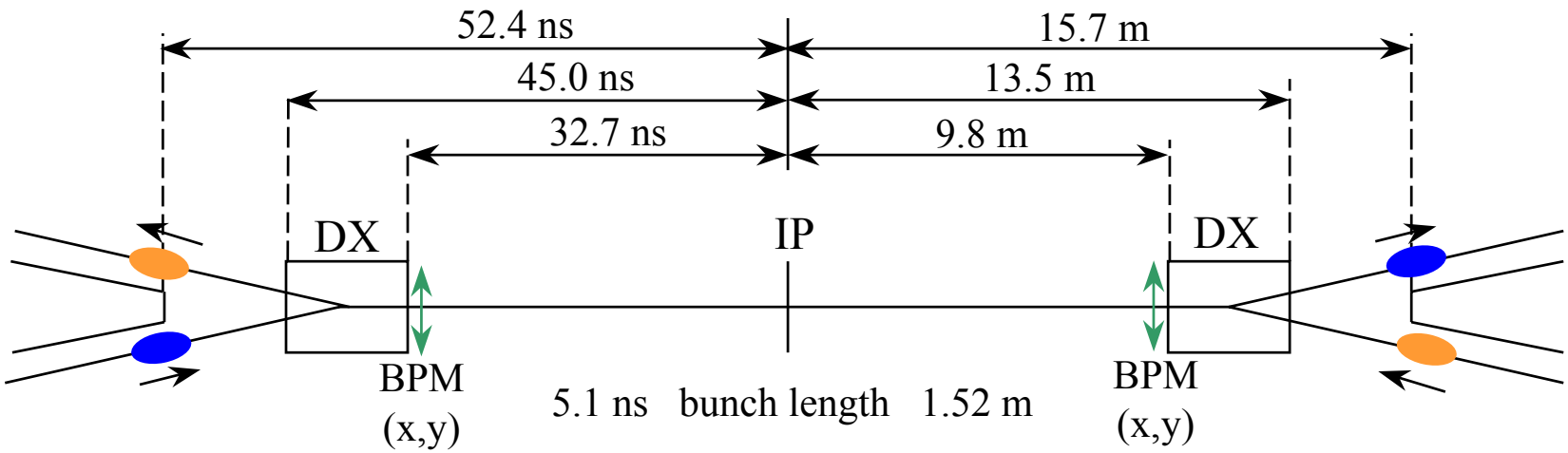
quantity	unit	accel. bunch	super bunch	
circumference C	m	3833		
beam-beam limit ΔQ_{max}	...	−0.03		← Optimistic
crossing angle θ	mrad	0.5		← Can be implemented now
lattice β^* at store	m	1.0		← Current value
relativistic γ at store	...	260		
emittance ε_N, 95%	μm	20		
interaction region length l	m	20		← With DX, can be much larger
eff. detector length l_{det}	m	0.7		← Current maximum
particles per bunch N_b	10^{11}	4.0	215	
number of bunches n_b	...	320	6	
bunch area S, 95%	eV·s	1.0	...	
rf frequency f_{rf}	MHz	28	...	
gap voltage V_{gap}	MV	0.3	...	← Existing accelerating system
rms bunch length σ_z	m	0.45	...	

	ISR	SPS	Tevatron Run I	HERAp	RHIC* pp	LHC
Bunches per beam	coasting	3	6	174	110	2808
Experiments	6	2	2	2	4	4
Parasitic interactions		4	10	—	—	120
ξ / IP	0.0010	0.0093	0.0075	0.0007	0.0074	0.0033
Total bb tune spread, max	0.008	0.028	0.024	0.0014	0.030	0.010

* Numbers for assuming ε_N=20μm and N_b=2 10^{11}

Sources: W. Schnell PAC75, W. Herr, V. Shiltsev, C. Montag

Bunch length and spacing for rf storage system (2520 buckets), 120 bunches (only 60 bunches in 2001)



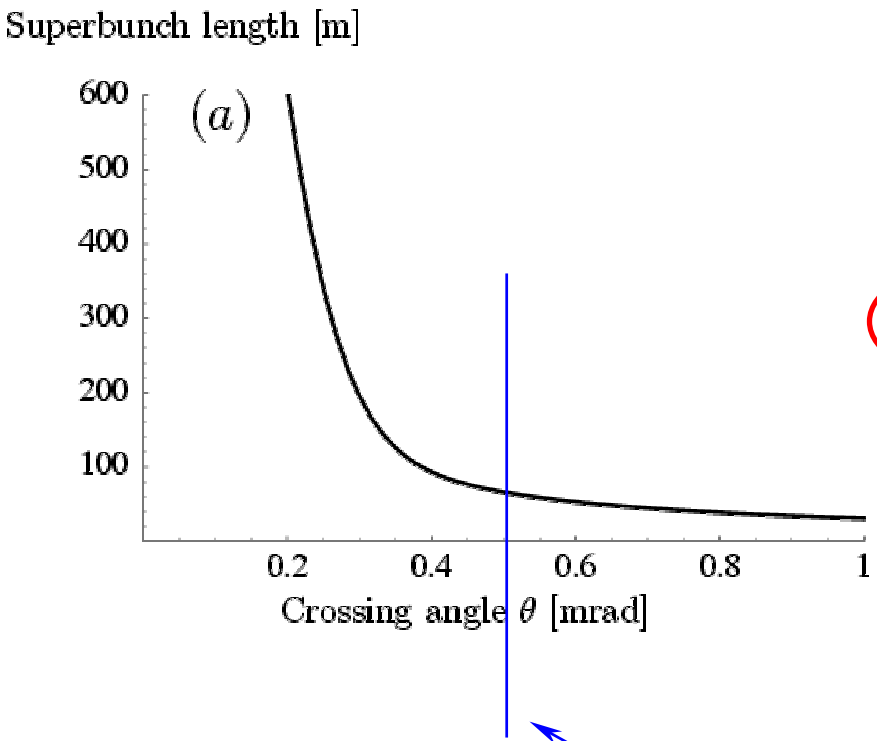
- Barrier cavities only for gap maintenance, not for acceleration

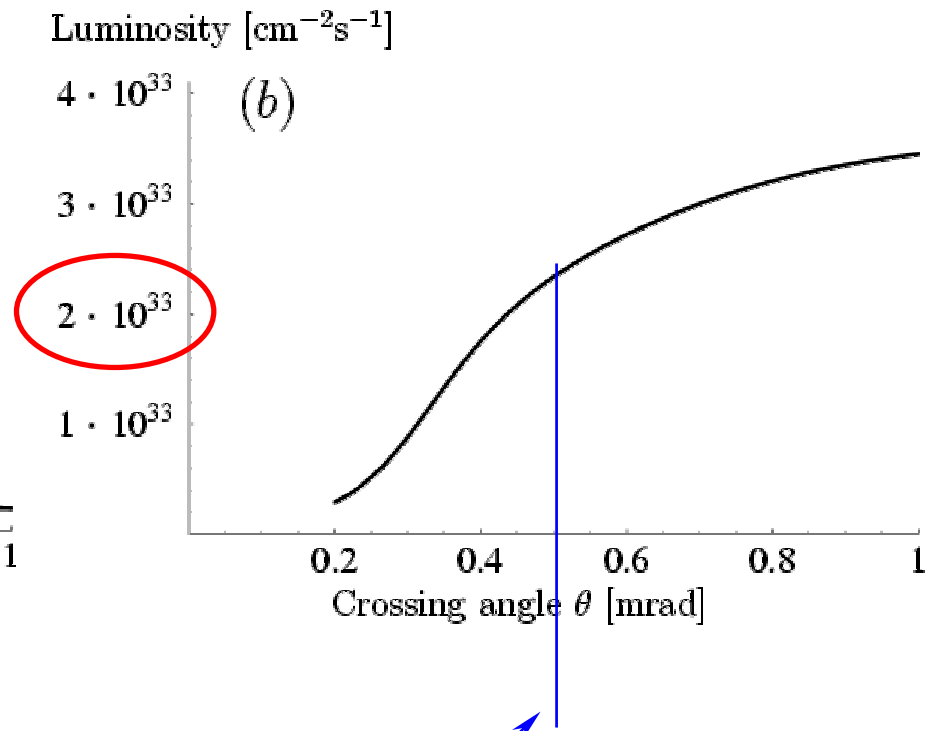
quantity	unit	injection	storage	
relativistic γ	...	26	260	
kinetic energy E_k	GeV	23.4	243.0	
slip factor η	...	0.00044	0.00191	
energy spread $\hat{\varepsilon}$	...	10^{-3}	10^{-3}	
barrier frequency f_{rf}	MHz	1.0	1.0	
gap voltage $\hat{V}$	kV	0.2	9	← feasible

- Required voltage appears feasible with existing experience (for example AGS, SPS)
- May need higher frequency (for shorter gaps) than used AGS barrier cavity (1 MHz → 1μsec gap)

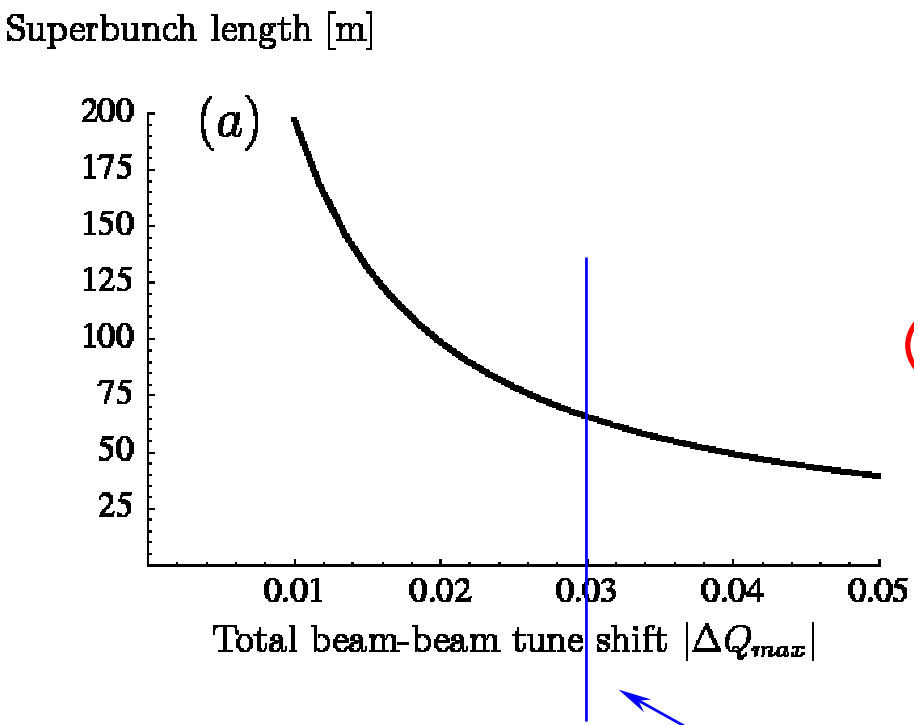
- Compress intensity into six superbunches until beam-beam limit ΔQ_{max} is reached
  $\rightarrow$ almost constant peak current (within superbunches)
  $\rightarrow$ maximizes luminosity
- Luminosity at the beam-beam limit

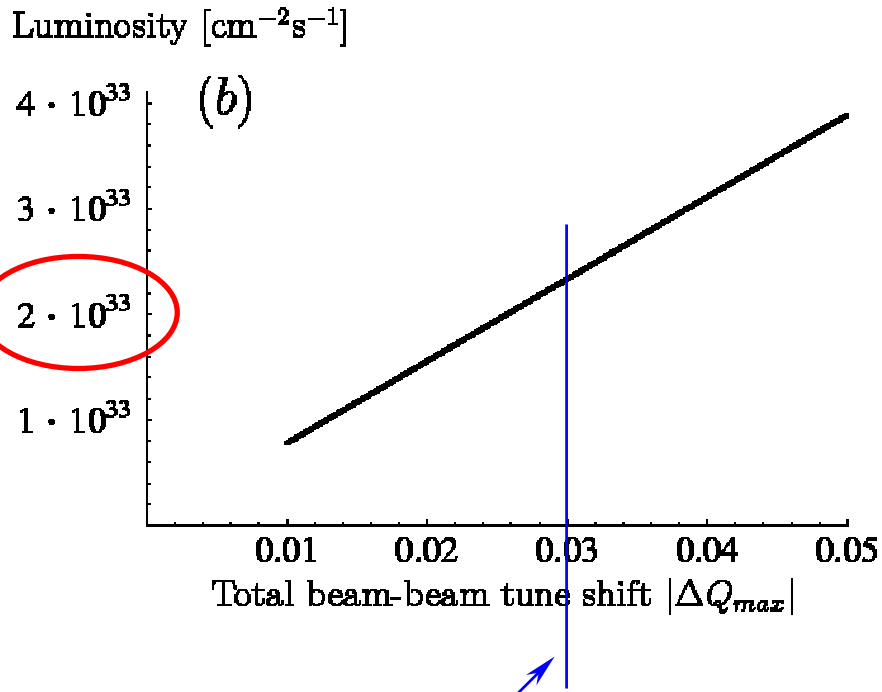
$$L = \frac{\gamma N_b n_b}{\beta^*} |\Delta Q_{max}| F(\theta, l, l_{det})$$





Base assumption for crossing angle
(can be implemented without additional hardware)





Base assumption for maximum beam-beam tune shift (optimistic)

- Estimated luminosity in RHIC with
  - 6 superbunches
  - 2 collisions
  - $N = 320 \cdot 4 \cdot 10^{11}$ per beam (25× current total intensity)
  - $\Delta Q_{max} = -0.03$ from beam-beam
- A luminosity of $L = 2 \cdot 10^{33}$ cm^{-2}s^{-1} is estimated
  → About 2 orders of magnitude higher than now (N_b=10^{11}, n_b=55)
  → About 50% higher than L with h = 360 buckets and same total intensity (N_b=$4 \cdot 10^{11}$, n_b=320)
- Barrier cavities needed for injection and superbunch compression at store, acceleration with h = 360
- More effects need to be studied for realistic estimate
  → detailed filling scheme, long-range interactions on ramp, resonances, coherent effects, superbunch end effects, beam-loading, IBS, other high-intensity effects