Colliding Beams

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BND School, Sept, 2015

Outline

- Introduction of collider
  - Type and History of collider
  - Collider performance
    - luminosity, its definition
    - optimization
- Beam dynamics Challenges of colliding beams
  - what is beam-beam force?
  - Beam-beam effect on beam dynammics
  - beam-beam compensation
- Measures to reach high luminosity performance
- Future colliders

Motivation of Colliders

The advantage of a collider is to reach higher energy. The center of mass energy of a two head on collision particles is

$$E_{cm} = \sqrt{m_1^2 + m_2^2 + 2E_1E_2(1+\beta_1\beta_2)}$$

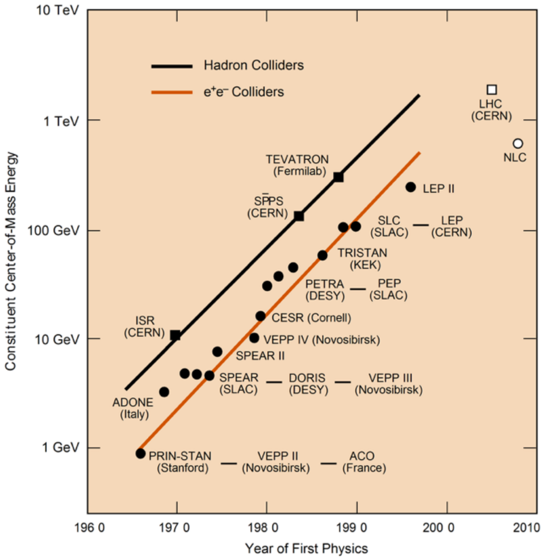
where E_1, E_2 are the energy of the two colliding beams, respectively. And, β_1 and β_2 are the Lorentz β of each beam. For two relativistic beam of the same particle with the same energy of E, the effective energy is simply $\sqrt{s} \simeq 2E$

Typically, collider is used to

- To discover new particles: HiggsLHC, Top quarkTevatron
- To explore the inner structure of matter quark-gluon plasma@RHIC, proton spin structure@RHIC and HERA

History of collider

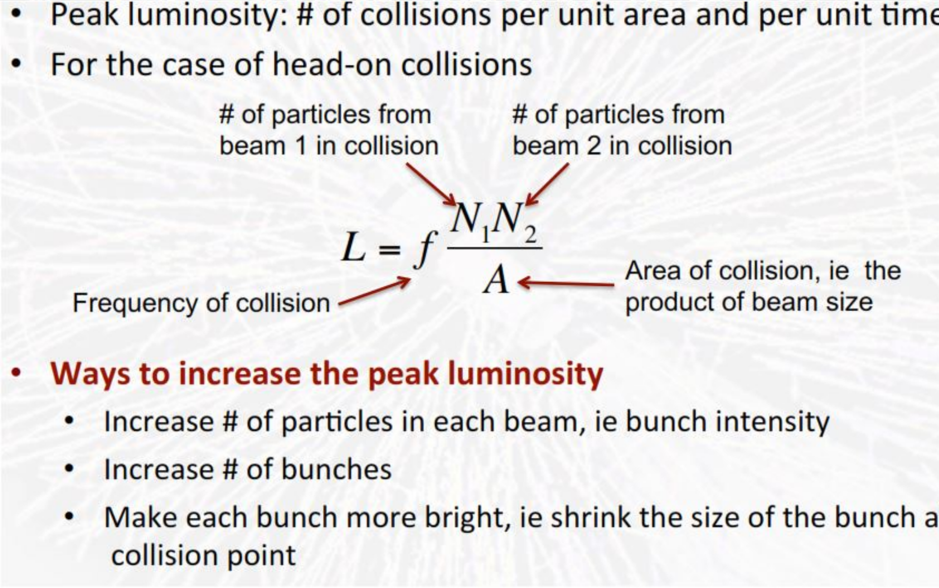
- orders of magnitude increase of energy over the past 40 years to
  - explore the fine structure of matter
  - to discover/produce heavier particles
- more lepton colliders than hadron colliders



List of Colliders

facility	location	type of collision	energy	year of oper.	legacy
ISR	CERN	p	31.5GeV	1971-1984	stochastic cooling
SppS	CERN	pbar	270GeV-315GeV	1981-1984	W,Z boson
PEP II	SLAC	e-e+	9GeV(e) 3.1GeV(e^+)	1998-2008	BaBar
SLC	SLAC	e-e+	45GeV	88-98	1st LC
CESR	Cornell	e-e+	6GeV	1979-2002	1st evidence B decay
B-factory	KEK	e-e+	8GeV(e) 3.5GeV e+	1999-	Belle
Tevatron	FNAL	p-pbar	900GeV 980GeV	1992-2001	top quark
HERA	DESY	e-p	e:27GeV p:920GeV	1992-2007	spin physics
RHIC	BNL	pp, d Au, U	255GeV 100GeV/c	2000-present	quark gluon plasma

Figure of merit of a typical collider



- Peak luminosity: # of collisions per unit area and per unit time
- For the case of head-on collisions

# of particles from beam 1 in collision

# of particles from beam 2 in collision

$$L = f\frac{N_1 N_2}{A}$$

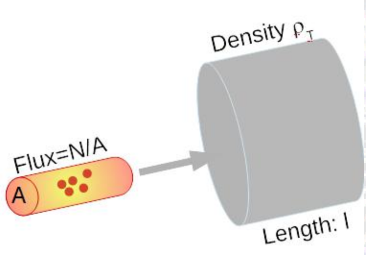
Frequency of collision

Area of collision, ie the product of beam size

- **Ways to increase the peak luminosity**
  - Increase # of particles in each beam, ie bunch intensity
  - Increase # of bunches
  - Make each bunch more bright, ie shrink the size of the bunch a collision point

What is Luminosity?

For a fixed target experiment,

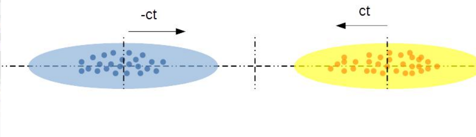


the event rate is given by

$$R = \frac{N}{A}\rho_T\sigma_T$$

where σT is the cross section of interaction. And, $L = \frac{N}{A}\rho_T$ is defined as luminosity

In a collider with two relativistic beams,



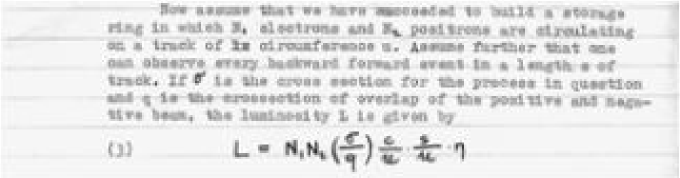
the luminosity is

$$L = \int\int\int\int_{-\infty}^{\infty} \rho_1(x, y, s - ct)$$
$$\rho_2(x, y, s + ct)2cdtdsdxdy.$$

The event rate of the collider is $R = L\sigma_c$ where σ_c is the interaction cross section

Luminosity and Legacy of B. Touschek

- the term of luminosity was first coined by Dr. Bruno Toucschek to describe the interaction rate in a collider [http://arxiv.org/pdf/1103.2727.pdf]



Now assume that we have succeeded to build a storage ring in which N_1 electrons and N_2 positrons are circulating on a track of ~~km~~ circumference u. Assume further that one can observe every backward forward event in a length s of track. If σ is the cross section for the process in question and q is the crossection of overlap of the positive and negative beam, the luminosity L is given by

$$L = N_1 N_2 \left(\frac{\sigma}{q}\right) \frac{c}{u} \cdot \frac{s}{u} \cdot \eta \qquad (3)$$

- Dr. Touschek was a particle physicist in INFN, Italy. Born and raised in Vienna, he became a physicist in Germany. A survivor of Kiel concentration camp, he was also known as the father of e+e- collider. In February 1960, he proposed and designed the first e+e- collider AdA with beam energy of 250MeV. His proposal was accepted, and funding of 8 million Lire was assigned.
- In 1963, he first observed the limitation of beam lifetime due to Coulomb scattering at AdA, aka Touschek effect[Phys. Rev. Lett., vol 10, #9, May 1963].

Thanks to Dr. Botlo(QuantBot LLC, who provided some materials on Dr. Touschek's work

What is Luminosity?

Typically, the unit of instant luminosity is $cm^{-2}s^{-1}$. For two round relativistic bunches head-on collision, the maximum peak luminosity is

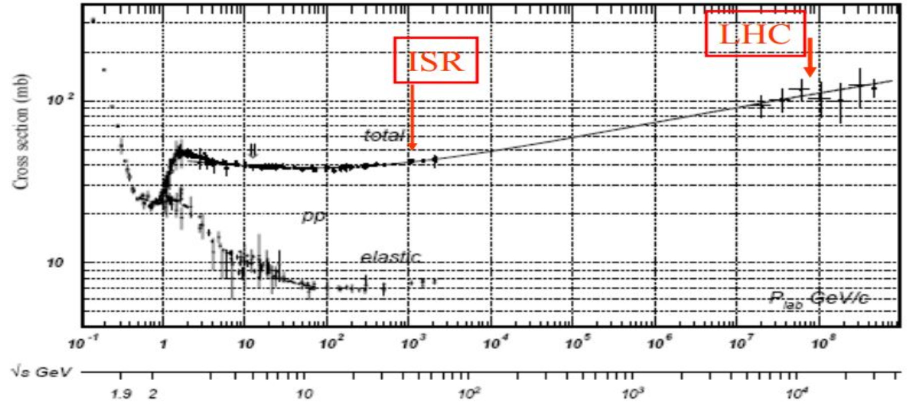
$$L = \frac{f_{rev} N_{col} N_1 N_2}{2\pi \sqrt{\sigma_{x_1}^2 + \sigma_{x_2}^2} \sqrt{\sigma_{y_1}^2 + \sigma_{y_2}^2}}$$

where f_{rev} is the orbital revolution frequency, N_{col} is the number of bunches in collision and $N_{1,2}$ is the bunch intensity for the two colliding beams, respectively. $\sigma_{x_{1,2},y_{1,2}}$ is the transverse beam size of the two beams, respectively.

	f_{rev} kHz	p GeV/c	N_{col}	$N_{1,2}$	$\epsilon_{1,2}$ mm-mrad	β^* [m]	L $cm^{-2}s^{-1}$
RHIC	78	250	110	$1.5x10^{11}$	$15x10^{-6}$	1	$3.8x10^{32}$
LHC	11.25	1000	2808	$1.2x10^{11}$	$14x10^{-6}$	0.5	$1x10^{34}$

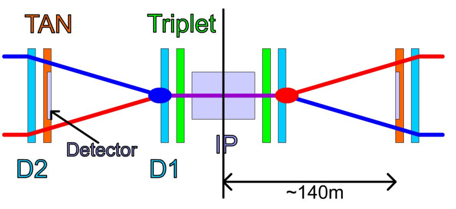
What are the event rates?

In a collider, the detector at each collision point is designed to detect certain interaction events when two beams are in collision and the event rate is the product of luminisoty and cross section of the interaction. For LHC, the total cross section is about 100 mbarns at 7 TeV, among which about 60 mbarns are inelastic interactions. This means at luminosity of $10^{34} cm^{-2} s^{-1}$, the detector seems about 600 million events per sec!



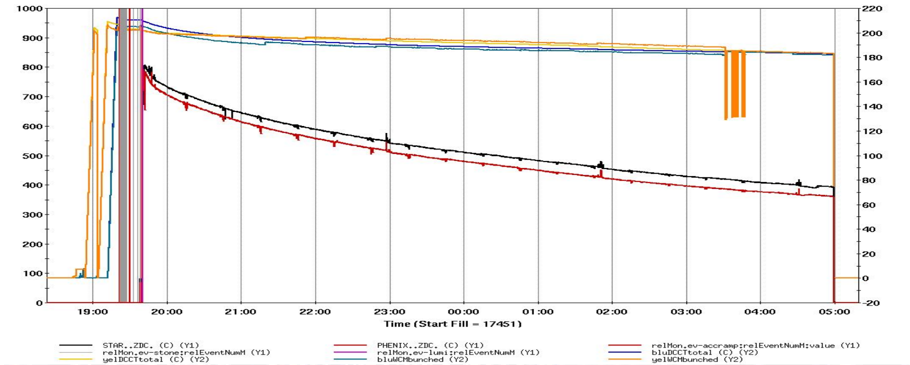
Luminosity monitor

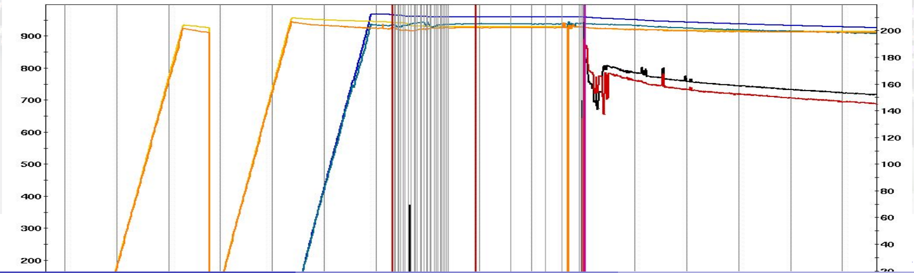
- indirect measurement by measuring all relevant beam parameters
    - very difficult to have all precisely measured
- direct measurement by measuring the event rate of a well-known interaction process with known/calculable cross-section
    - for e+e- collider, often use the small angle electron elastic scattering, aka Bahaha scattering
    - for hadron collider, often use Zero Degree Calorimeter to detect the neutrons from collisions



http://ab-dep-bi-pm.web.cern.ch/ab-dep-bi-pm/?n=Activities.BRAN"

A typical store of RHIC polarized proton





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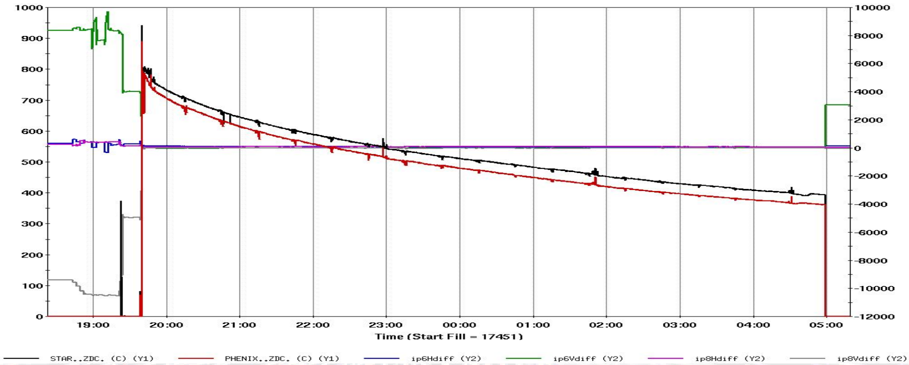
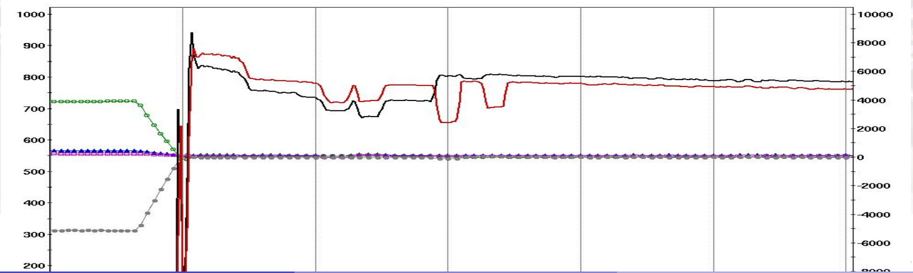
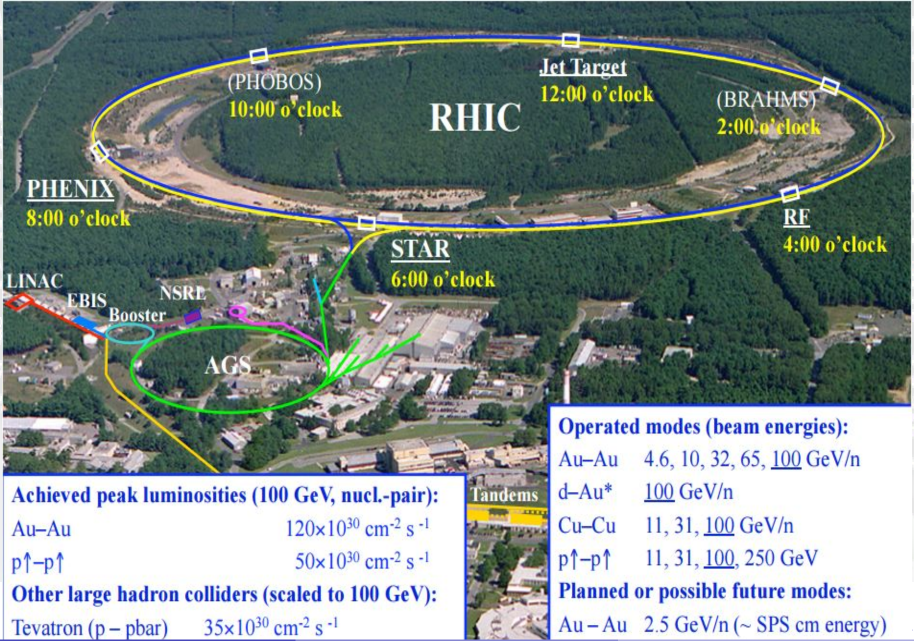




Luminosity performance of colliders: RHIC



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	50×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	35×10^{30} cm^{-2} s^{-1}

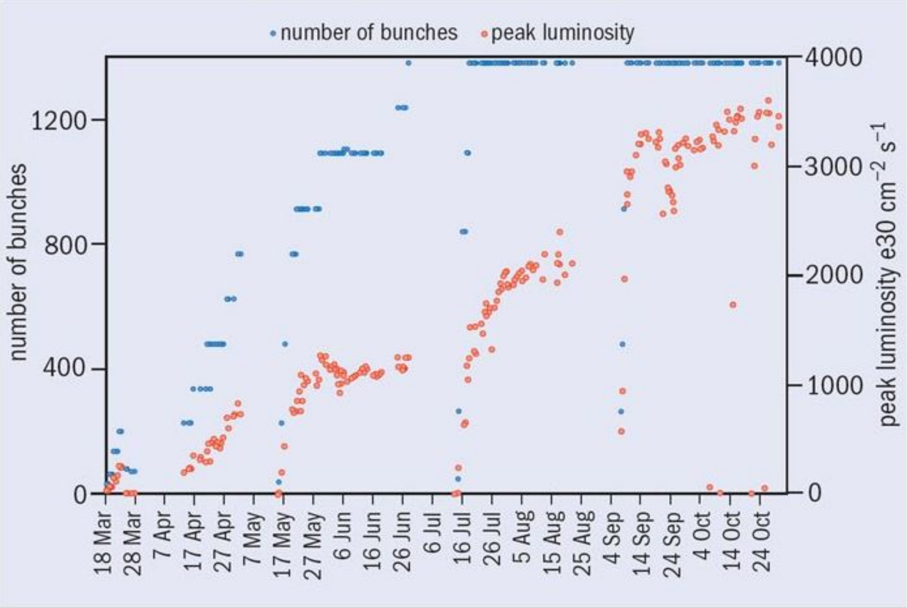
Operated modes (beam energies):

Au–Au	4.6, 10, 32, 65, 100 GeV/n
d–Au*	100 GeV/n
Cu–Cu	11, 31, 100 GeV/n
p↑–p↑	11, 31, 100, 250 GeV

Planned or possible future modes:

Au – Au	2.5 GeV/n (~ SPS cm energy)

Luminosity performance of colliders: LHC



Performance 2011 – in red the peak luminosity, in blue the number of bunches. The plot tracks the switch to 50 ns bunch

Integrated luminosity

is defined as total number of collision events within the duration of a store

$$L_{int} = \int_0^{T_{store}} L(t)dt$$

The unit of integrated luminosity is the inverse of cross-section unit, and typically expressed in inverse barn ($10^{-24} cm^{-2} s^{-1}$). For instance, RHIC delivered about 540 pb^{-1} of about 4 month polarized proton operation in 2013.

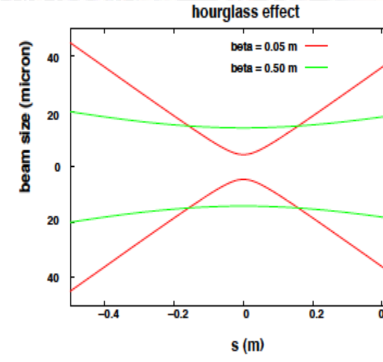
In additional to the direct burn-off rate of collisions, the integrated luminosity is directly affected by

- how effective is the detector: vertex distribution, detector ramp-up time, etc.
- beam emittance growth during store due to various diffusion mechanisms such as intra-beam scattering, beam-beam effect, orbital resonance, etc.
- overall percentage of time-in-store

hour-glass effect

In reality, bunch has non-zero length and hour-glass shaped transverse beam profile, the effective luminosity is further reduced. The beam transverse size evolves as

$$\sigma(s) = \sigma^\star \sqrt{1 + (\frac{s}{\beta^\star})^2}$$



and for Gaussian distributed round beam, the effective luminosity then becomes

$$L = \int_{-\infty}^{\infty} \frac{1}{\sqrt{\pi}} e^{-\frac{u^2}{2\sigma^2}} \frac{1}{1 + (\frac{u}{u_0})^2} du = \sqrt{\pi} \frac{\beta^\star}{\sigma^\star} e^{(\frac{\beta^\star}{\sigma^\star})^2} erfc(\frac{\beta^\star}{\sigma^\star}) L_0$$

where L_0 is the luminosity with out hour glass.

Effect of collisions on Beam Dynamics

- Beam-beam effect

$$2\pi r E_r = \frac{1}{\epsilon_0}\int_0^r 2\pi r' \rho(r') dr'$$

and

$$2\pi r B_\phi = \mu_0 \int_0^r 2\pi r' \beta c \rho(r') dr'$$

- in the case of round beam with Gaussian distribution $\rho(x,y) = \frac{nq}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2}}$

$$2\pi r E_r = \frac{1}{\epsilon_0}\int_0 r \frac{2\pi n q r'}{2\pi\sigma^2} e^{-\frac{r'^2}{2\sigma^2}} dr' = \frac{nq}{\epsilon_0}[1 - e^{-\frac{r^2}{2\sigma^2}}]$$

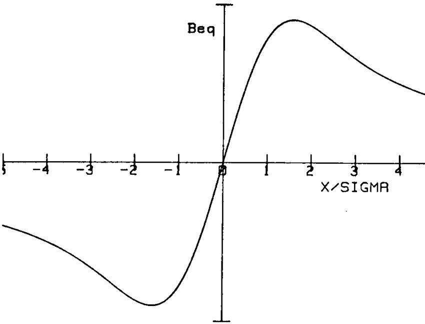
Beam-beam force

For a Gaussian beam, the beam-beam force is given by

$$F_r(r) = -\frac{nq^2(1+\beta^2)}{4\pi\epsilon_0\sigma^2}(1 - e^{-r^2/2\sigma^2})$$

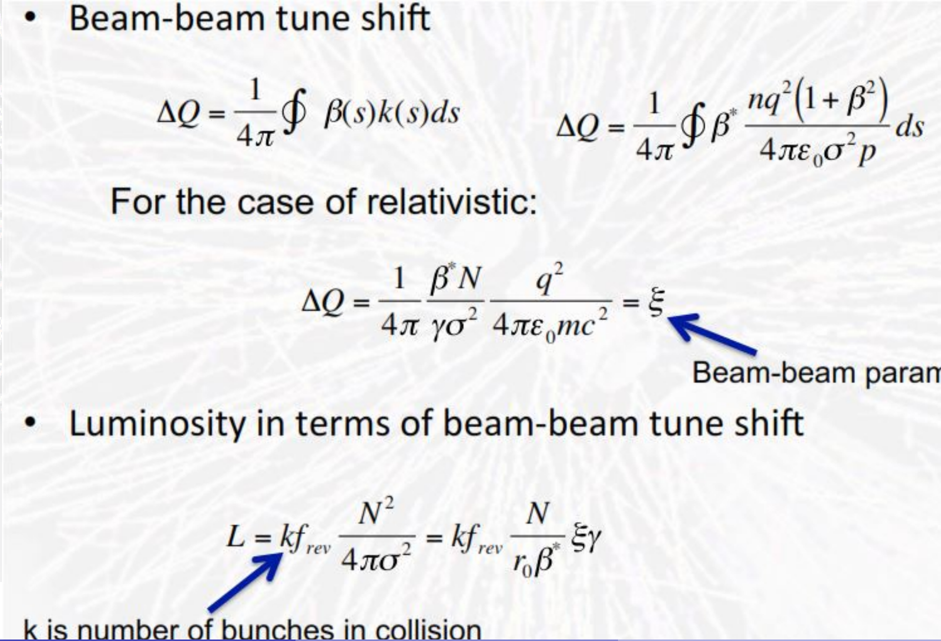
$$F_r(r) = -\frac{nq^2(1+\beta^2)r}{4\pi\epsilon_0\sigma^2} \text{ for } r << \sigma$$

$$F_r(r) = -\frac{nq^2(1+\beta^2)r}{2\pi\epsilon_0 r} \text{ for } r >> \sigma$$



- nearby beam center, beam-beam force is rather linear, quadrupole-like
- away from beam center, beam-beam effect becomes rather non-linear, which introduces betatron amplitude dependent focusing force
- beam-beam force is independent to beam energy

beam dynamics in the presence of beam-beam



- Beam-beam tune shift

$$\Delta Q = \frac{1}{4\pi}\oint \beta(s)k(s)ds \qquad \Delta Q = \frac{1}{4\pi}\oint \beta^{*}\frac{nq^{2}\left(1+\beta^{2}\right)}{4\pi\varepsilon_{0}\sigma^{2}p}ds$$

For the case of relativistic:

$$\Delta Q = \frac{1}{4\pi}\frac{\beta^{*}N}{\gamma\sigma^{2}}\frac{q^{2}}{4\pi\varepsilon_{0}mc^{2}} = \xi$$

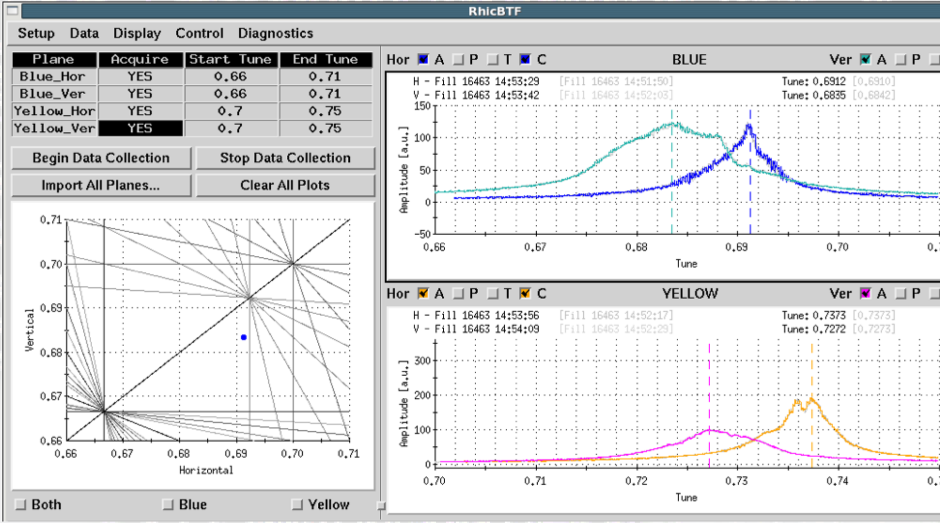
Beam-beam param

- Luminosity in terms of beam-beam tune shift

$$L = kf_{rev}\frac{N^{2}}{4\pi\sigma^{2}} = kf_{rev}\frac{N}{r_{0}\beta^{*}}\xi\gamma$$

k is number of bunches in collision

Beam Transfer Function with beam-beam



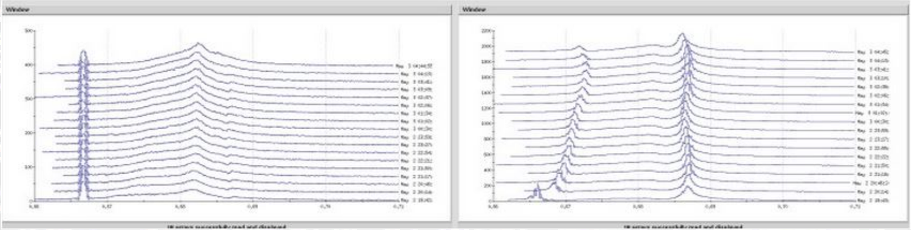
Plane	Acquire	Start Tune	End Tune
Blue_Hor	YES	0.66	0.71
Blue_Ver	YES	0.66	0.71
Yellow_Hor	YES	0.7	0.75
Yellow_Ver	YES	0.7	0.75

```
H - Fill 16463 14:53:29   [Fill 16463 14:51:50]   Tune: 0.6912 [0.6910]
V - Fill 16463 14:53:42   [Fill 16463 14:52:03]   Tune: 0.6835 [0.6842]
```

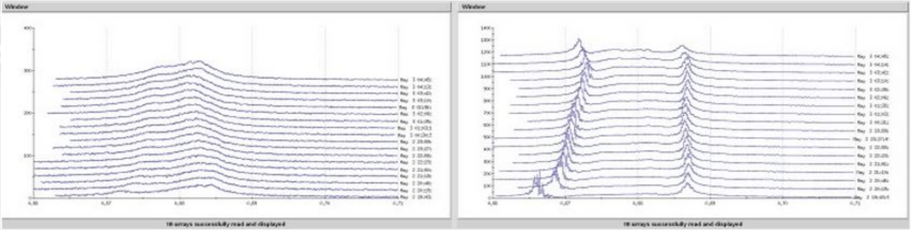
```
H - Fill 16463 14:53:56   [Fill 16463 14:52:17]   Tune: 0.7373 [0.7373]
V - Fill 16463 14:54:09   [Fill 16463 14:52:29]   Tune: 0.7272 [0.7273]
```

Beam Transfer Function of a typical RHIC store

Blue ring



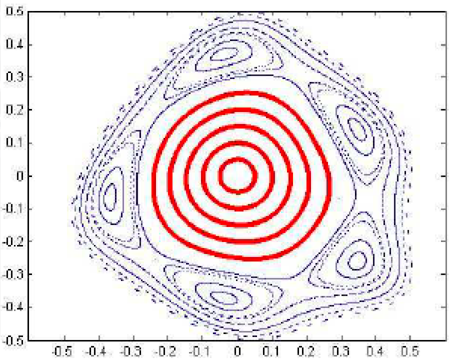
Yellow ring

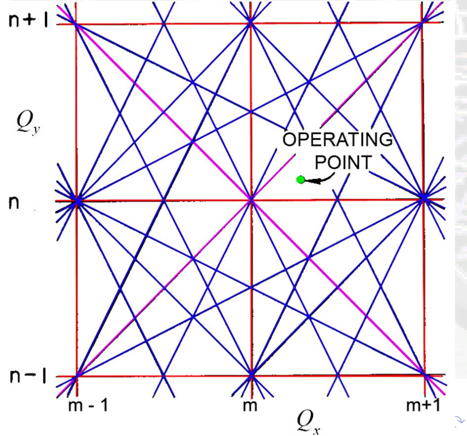


Challenge in reaching high luminosity

- increase bunch intensity, which results in higher beam-beam tune shift/spread. This can then cause either poor beam lifetime or less brighter beam due to emittance growth, and result in lower luminosity

Betatron resonance: $MQ_x + NQ_y = K$





Resonance Mechanism

- errors in an accelerator perturbs beam motion
- coherent buildup of these perturbations can lead to the instability of beam motion, resonant condition

Driven harmonic oscillator

- Equation of motion

$$\frac{d^2x(t)}{dt^2} + \omega^2 x(t) = f(t) = \sum_{m=0} C_m e^{i\omega_m t}$$

- for $f(t) = C_M e^{i\omega_m t}$

$$\frac{d^2x(t)}{dt^2} + \omega^2 x(t) = f(t) = C_m e^{i\omega_m t}$$

- Assume solution is like $x(t) = Ae^{i\omega t} + A_m e^{i\omega_m t}$
- and the response of the harmonic oscillator is

$$x(t) = Ae^{i\omega t} + \frac{C_m}{\omega^2 - \omega_m^2} e^{i\omega_m t}$$

Betatron oscillation

- in the presence of errors including field errors, the equation of motion becomes

  $$x'' + K(s)x = -\frac{\Delta B_y}{B\rho}$$

  where, $\Delta B_y = B_0(b_0 + b_1 x + b_2 x^2 + \dots)$. And, b_0 is the dipole error, b_1 is the quadrupole error and b_2 is the sextupole error. Here, $K(s + L_p) = K(s)$
- let's re-define $\zeta(s) = x(s)/sqrt(\beta_x(s))$, and $\phi(s) = \psi(s)/Q_x$ or $\phi' = 1/(Q_x\beta_x)$, then the equation of motion becomes

  $$\frac{d^2\zeta}{\phi^2} + Q_x^2\zeta = -Q_x^2\beta_x^{3/2}\frac{\Delta B_y}{B\rho}$$

  $$\frac{d^2\zeta}{\phi^2} + Q_x^2\zeta = -\frac{Q_x^2 B_0}{B\rho}[b_0 + \beta_x b_1\zeta + \beta_x^2 b_2\zeta^2 + \beta_x^n b_n\zeta^n + \dots]$$

Betatron oscillation cont'd

- for each n,

$$\frac{d^2\zeta}{\phi^2} + Q_x^2\zeta = -\frac{Q_x^2\beta_x^{3/2}}{B\rho}\beta_x^n b_n\zeta^n$$

- put $\zeta = e^{-iQ_x\phi}$ the solution of the homogeneous differential equation to the right side of the above equation, one then gets

$$\frac{d^2\zeta}{\phi^2} + Q_x^2\zeta = -\frac{Q_x^2\beta_x^{3/2}}{B\rho}\beta_x^n b_n e^{-inQ_x\phi}$$

- for an accelerator with periodic structure, one can expand $\beta_x^{(n+3)/2}b_n = \sum_k C_k e^{ikf}$, and the equation of motion becomes

$$\frac{d^2\zeta}{\phi^2} + Q_x^2\zeta = -\frac{Q_x^2}{B\rho}\sum_k e^{i(k-nQ_x)\phi}$$

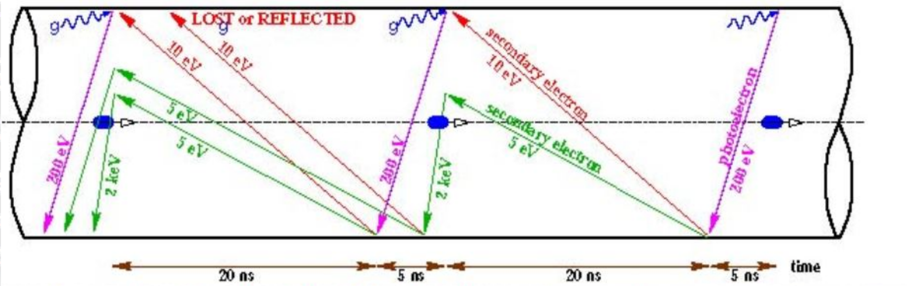
Resonance

- this means the betatron motion becomes unstable, i.e. on resonance, when $Q_x = \pm(k - nQ_x)$
  - in other words, the resonance locations are $(n+1)Q_x = k$, and $(n-1)Q_x = k$, for $k! = 0$
- any error of x^n can drive a $(n+1)^{th}$ order resonance. Dipole error drives the 1^{st} order resonance, quadrupole error drives the 2^{nd} order resonance, sextupole error drives the 3^{rd} order resonance and octupole error drives the 4^{th} order resonance
- and driving term is then given by

$$C_{k,n} = \frac{1}{B\rho}\frac{1}{2\pi Q_x}\int_0^{circ} \beta_x^{(n+1)/2}(s) b_n(s) e^{ik\phi} ds$$

Issues of higher bunch intensity

Brighter beam can also include electron cloud, which in turn provides additional non-linear force on each particle in the beam, and can cause beam instability, slow beam loss, emittance growth



schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

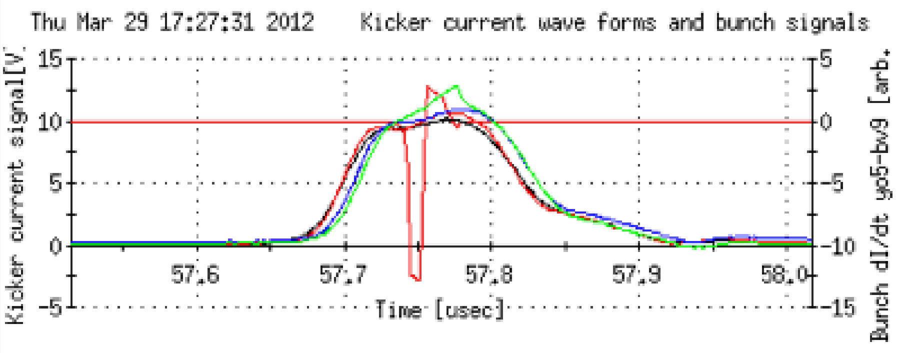
Mitigation: NEG coating vacuum pipe

[F. Ruggiero]

Increasing # of bunches

is also limited by

- available RF buckets
- injection kicker



Issues of further beta squeeze

- large beta functions at triplet, three quadrupoles in series on either side of the interaction point. Further beta squeeze can cause lower luminosity due to
  - physical limit of triplet
  - particles sample large unwanted magnetic fields, which drive higher order resonances and cause poor beam lifetime and emittance growth
- becomes less effective when beta function at the interaction point becomes less than the bunch length (hour-glass effect)

mitigate beam-beam limit

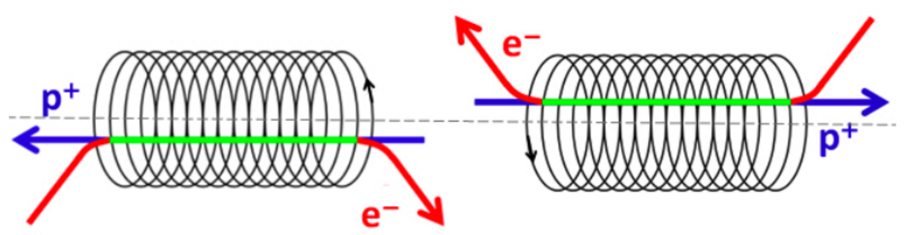
- carefully choose working point, i.e. lattice tunes for collision, on the tune diagram in an area with maximum space between harmful betatron resonances
- correct harmful betatron resonances. very difficult due to
  - parasitic measure of high order resonance driving terms
  - imperfect match between the lattice model and real machine to find the perfect knob
- minimize beam-beam effect
  - provide large crossing angle between the two beams. However, this also directly reduces the luminosity by

$$L \simeq L_0 \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} tan\frac{\theta}{den})^2}} \tag{1}$$

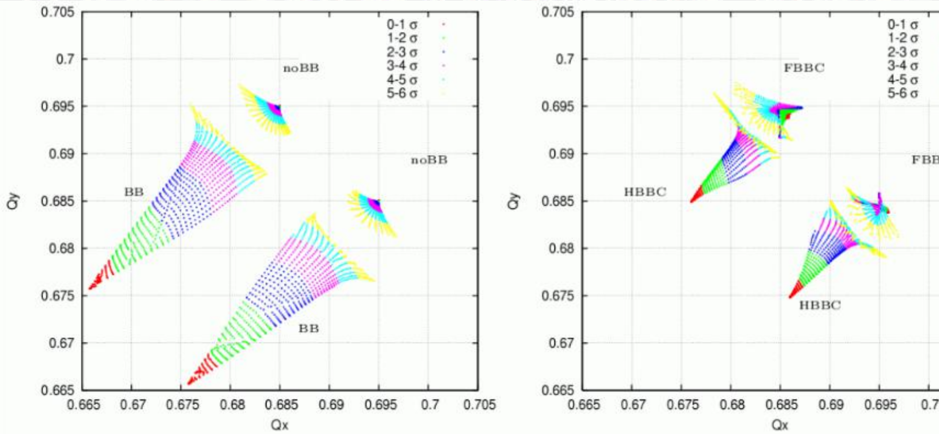
- compensate beam-beam effect
  - electron lens for compensating head-on collisions in a pp collider

Electron Lens

- not possible to compensate beam-beam with magnet
- use a low energy matched electron beam at a preferred betatron phase to the collision point to compensate the beam-beam tune spread so that the same area in the tune diagram can accommodate more particles
- was first proposed and tested at Tevatron
- adapted by RHIC, and is under commissioning

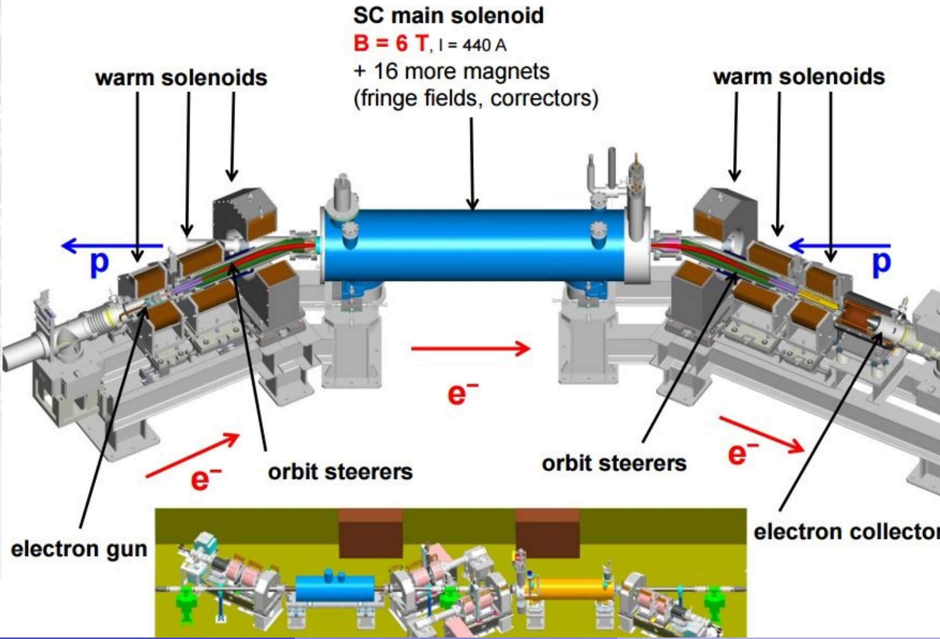


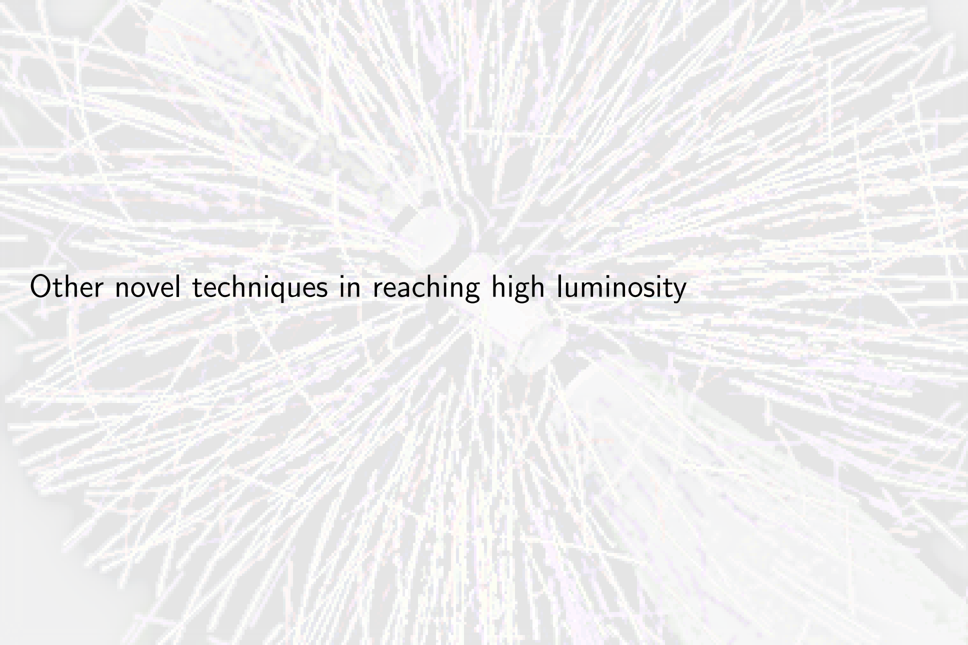
beam-beam tune spread w./w.o Elens



– simulation by Y. Luo, BNL

RHIC electron lenses

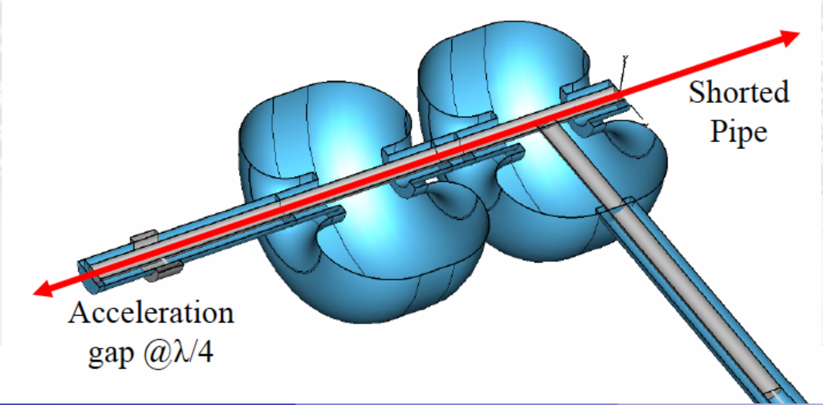




Other novel techniques in reaching high luminosity

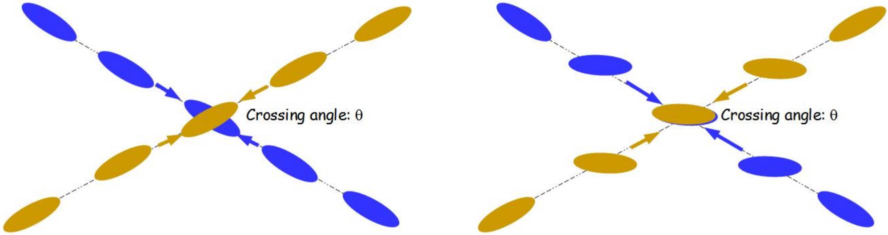
Mitigating E-cloud

- neg-coating beam pipes to reduce secondary electron yield
- longer bunch length to reduce bunch peak current during acceleration. For RHIC, an 9 MHz cavity is used to accelerator polarized protons. It not only provides better longitudinal matching at injection, but also provide 3 times longer bucket to avoid emittance growth due to E-cloud



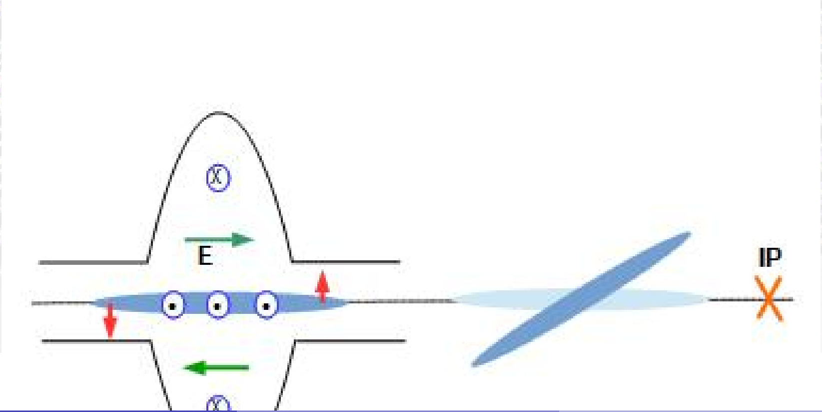
Crab Crossing

- large crossing angle can reduce beam-beam effect. However, it also reduces luminosity
- use RF cavity on either side of the collision point to align the bunch shape of the two beams to recover luminosity reduction due to geometric factor. Such a cavity is called crab cavity

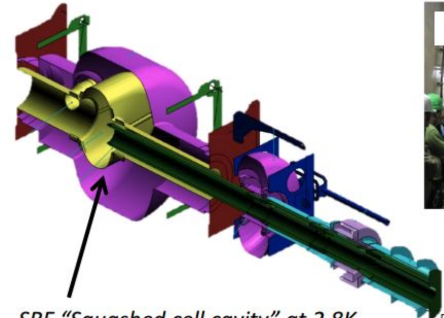


Crab cavity

- First introduced by Dr. R. Palmer (BNL) in 1988 and first demonstrated at KEK B-factory in 2007
- An RF device operates at TM110 mode that provides phase dependent transverse kickes to tilt the bunch. The size of the tilt is proportionally to the strength of the maximum field of the cavity and distance between cavity to IP



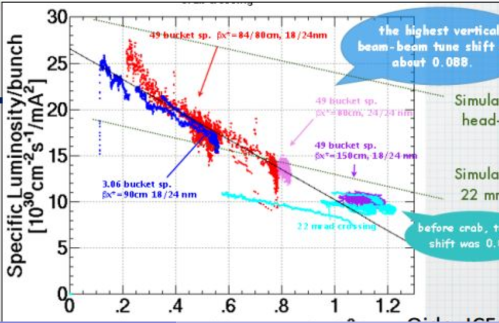
KEKB crab cavity



SRF "Squashed cell cavity" at 2.8K
with crabbing mode at 500 MHz
(2.8 MV defl voltage)

- ~ 3 years operation under high current
- L_{peak} =21.1 x 10^{33} /cm²/s (with crabs)

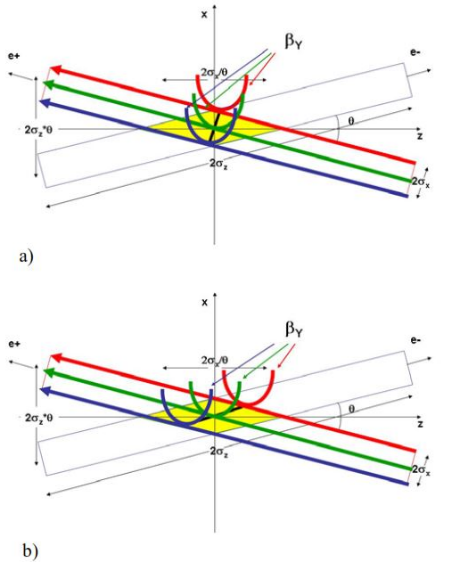
KEKB operation terminated in June 2010
for the upgrade towards SuperKEKB



Crab waist

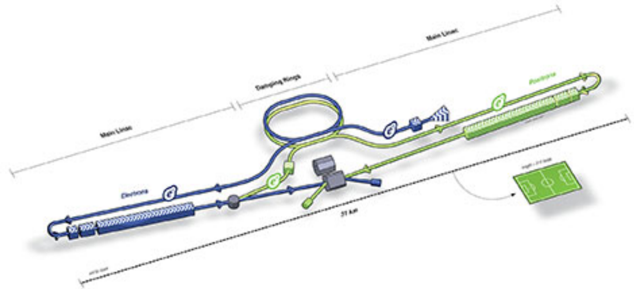
- for a collider with two flat beams in collision, one can use large horizontal crossing angle to reduce parasitic collision as well as beam-beam tune shift
- one can use a sextupole on either side of the collision point to re-distribute the beta squeeze waist in the overlap area of the two beams. The beta function at the waist then becomes

$$\beta(s) = \beta^* + \frac{(s - x/\theta)^2}{\beta^*}$$



Future collider projects/proposals

- Higgs factory
  - international linear collider (ILC) to collide e+e- at an energy of 500 GeV
    - 16,000 super conducting cavity LINAC



  - circular e+e- collider:
    - Future Circular Collider (FCC)-ee: CERN proposal of a 100 km collider at energy of z-pole up to top-peak
    - China Electron Positron Collider (CEPC): Chinese propsal of 54 km collider

Future collider projects/proposals

- super proton proton collider
  - Future Circular Collider (FCC) from CERN: 100 km at energy of 100 TeV
  - SPPC: chinese proposal of 54 km at energy of 100 TeV
- electron ion collider
  - eRHIC: adding a 23 GeV polarized electron beam using multiturn ERL to existing RHIC polarized proton/heavy ion accelerator
  - MEIC: establish Fig-8 ring complex to accelerate and collide polarized electron against polarized protons, deuterons, as well as He-3
  - LHeC: adding 60GeV polarized electron beam to the existing LHC proton beams