Implementation of Round Colliding Beams Concept at VEPP-2000

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JAI, Oxford
Introduction

Beam-Beam Effects
Circular colliders

Different schemes:
- Single ring / two rings
- Multibunch beams
- Number of IPs
- Head-on / crossing angle

Low-beta insertion
(Interaction Region – IR)
## Colliders

### in operation:

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>pp, PbPb</td>
<td>7 TeV, 2.8 TeV/n</td>
<td>$1 \times 10^{34}$ cm$^{-2}$s$^{-1}$, $1 \times 10^{27}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>RHIC</td>
<td>pp, AuAu</td>
<td>250 GeV, 100 GeV/n</td>
<td>$1 \times 10^{32}$ cm$^{-2}$s$^{-1}$, $1.5 \times 10^{27}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>DAFNE</td>
<td>e$^+$,e$^-$</td>
<td>0.5 GeV</td>
<td>$4 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>BEPC-II</td>
<td>e$^+$,e$^-$</td>
<td>1.89 GeV</td>
<td>$7 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>VEPP-4M</td>
<td>e$^+$,e$^-$</td>
<td>5.5 GeV</td>
<td>$2 \times 10^{31}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>VEPP-2000</td>
<td>e$^+$,e$^-$</td>
<td>1 GeV</td>
<td>$1 \times 10^{32}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

### under construction:

<table>
<thead>
<tr>
<th>Collider</th>
<th>Type</th>
<th>Energy</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperKEKB</td>
<td>e$^+$,e$^-$</td>
<td>4×7 TeV</td>
<td>$8 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>NICA</td>
<td>AuAu</td>
<td>4.5 GeV/n</td>
<td>$1 \times 10^{27}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

### stopped:

- AdA (1961) – first collider (e$^+$,e$^-$)
- ISR (1971) – first hadron collider (pp)
- SLC (1988) – first (and only) linear collider
- LEP (1988) – highest energy e$^+$,e$^-$ collider (104.6 GeV)
- HERA (1992) – first (and only) electron-ion collider
- KEKB (1999) – highest luminosity collider ($2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$)
Luminosity

Number of events per second: \( \dot{N} = L \cdot \sigma_{\text{process}} \)

\[
L = 2n_b f_0 c \iiint \rho_1(x, z, s - ct) \rho_2(x, z, s + ct) dx dz ds dt
\]

For Gaussian distributions, non-equal beam profiles:

\[
L = \frac{N_1 N_2 n_b f_0}{2\pi \sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1z}^2 + \sigma_{2z}^2)}}
\]

\[
\rho(y) = \frac{1}{\sigma_y \sqrt{2\pi}} e^{-\frac{y^2}{2\sigma_y^2}}
\]

\[
y = x, z, s
\]

How many interacts?

\[
\frac{L \cdot \sigma_{\text{process}}}{f_0} \sim \frac{10^{32} \text{ cm}^{-2} \text{ s}^{-1} \cdot 10^{-24} \text{ cm}^2}{12 \cdot 10^6 \text{ Hz}} \sim 10
\]

Compare to \( N_{\text{bunch}} \sim 10^{11} \)

Other particles do not interact with each other but with opposite bunch field
Linear beam-beam effects

Beam-beam force for Gaussian bunches

Perturbation: thin axisymmetric linear lens.

\[
M = \begin{pmatrix}
\cos \mu_0 + \alpha_0 \sin \mu_0 & \beta_0 \sin \mu_0 \\
-\gamma_0 \sin \mu_0 & \cos \mu_0 - \alpha_0 \sin \mu_0
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-p & 1
\end{pmatrix}
\]

\[
= \begin{pmatrix}
\cos \mu_0 + \alpha_0 \sin \mu_0 - \beta_0 p \sin \mu_0 & \beta_0 \sin \mu_0 \\
-\gamma_0 \sin \mu_0 - p \cos \mu_0 + \alpha_0 p \sin \mu_0 & \cos \mu_0 - \alpha_0 \sin \mu_0
\end{pmatrix}
\]

Linear focusing

The sign depends on particles type. Focusing for particle-antiparticle beams.
Linear beam-beam effects (2)

\[ \frac{1}{2} \text{Tr}(M) = \cos \mu = \cos \mu_0 - \frac{1}{2} \beta p \sin \mu_0 \]

\[ \mu = \mu_0 + \Delta \mu \quad \Delta \mu << 1 \]

\[ \cos \mu \approx \cos \mu_0 - \Delta \mu \cdot \sin \mu_0 \]

\[ \Delta \mu = \beta_0 p / 2 \]

\[ \Delta \nu \approx \frac{\beta^* p}{4\pi} = \xi \quad \text{Beam-beam parameter} \]

\[ \xi_{x,z} = \frac{N_2 r_c \beta^*_{x,z}}{2\pi \gamma \sigma_{x,z} (\sigma_x + \sigma_z)} \]

\[ \cos \mu = \cos \mu_0 - 2\pi \xi \sin \mu_0 \]

\[ \Delta \nu = \frac{1}{2\pi} \arccos(\cos \mu_0 - 2\pi \xi \sin \mu_0) - \nu_0 \]
Dynamic beta

\[
\cos \mu = \cos \mu_0 - 2\pi\xi \sin \mu_0 \\
\beta \sin \mu = \beta_0 \sin \mu_0
\]

\[
\beta = \frac{\beta_0 \sin \mu_0}{\sqrt{1 - (\cos \mu_0 - 2\pi\xi \sin \mu_0)^2}} = \frac{\beta_0 \sin \mu_0}{\sqrt{\sin^2 \mu_0 + 4\pi\xi \cos \mu_0 \sin \mu_0 - (2\pi\xi)^2 \sin^2 \mu_0}} = \frac{\beta_0}{\sqrt{1 + 4\pi\xi \cot \mu_0 - (2\pi\xi)^2}}
\]

(1960s)

One of the reasons to choose working point close to half-integer resonance: additional (dynamic) bonus final focusing
Dynamic emittance

(1990s)

In electron synchrotron radiative beam emittance:

\[ \varepsilon_x = \frac{55}{32\sqrt{3}} \frac{\lambda_e}{J_x} \left\langle \frac{H}{r_0^3} \right\rangle \gamma^2 \]

\[ H(s) = \gamma_x(s)D(s)^2 + 2\alpha_x(s)D(s)D'(s) + \beta_x(s)D'(s)^2 \]

Perturbed \( \beta \)-function (dynamic beta) propagates to arcs and modifies \( H(s) \).

VEPP-2000 examples
Dynamic beta & emittance

Beam profile monitors at VEPP-2000

44 × 44 mA²

2 × 2 mA²
Flip-flop (simple linear example)

Assume round beams, unperturbed emittance

\[
\begin{align*}
\cos \mu_1 &= \cos \mu_0 - 2\pi \xi_2 \sin \mu_0 \\
\beta_1 \sin \mu_1 &= \beta_0 \sin \mu_0
\end{align*}
\]

\[
\left( \frac{\beta_0}{\beta_1} \right)^2 = 1 + 4\pi \xi_0 \cot \mu_0 \frac{\beta_0}{\beta_2} - \left(2\pi \xi_0 \right)^2 \left( \frac{\beta_0}{\beta_2} \right)^2
\]

\[
\xi_2 = \frac{N_r \beta_0^*}{4\pi \gamma \sigma_2^2} = \frac{N_r \beta_0^*}{4\pi \gamma \sigma_0^2} \left( \frac{\sigma_0}{\sigma_2} \right)^2 = \xi_0 \left( \frac{\beta_0}{\beta_2} \right)^2
\]

\[
\begin{align*}
2b_1^2 &= 1 + 4\pi \xi_0 \cot \mu_0 b_2 - \left(2\pi \xi_0 \right)^2 b_2^2 \\
b_2^2 &= 1 + 4\pi \xi_0 \cot \mu_0 b_1 - \left(2\pi \xi_0 \right)^2 b_1^2
\end{align*}
\]

Self-consistent solutions:
equal sizes below threshold \(\xi\),
non-equal above \(\xi_{th}\).
**Coherent beam-beam**

Two beams modes coupling via beam-beam interaction: new eigenmodes.

\[ \sigma \text{-mode, unperturbed tune, } \nu_\sigma = \nu_0 \]

\[ \pi \text{-mode, shifted tune, } \nu_\pi = \nu_0 + \Delta \nu_0 = \nu_0 + \lambda \xi \]

Without going into details, \( \xi \sim 1 \)

K. Hirata, 1988
Coherent beam-beam

Example: coherent beam-beam modes monitoring at VEPP-2000.

Shifted tune drift with beam current decay.
Beam-beam tune spread

LHC example:
pp − defocusing

Linear beam-beam:
tune shift

Nonlinear beam-beam:
tune spread (footprint)
Beam-beam limit

Beam-beam parameter saturation, emittance (and beam size) growth

\[ \xi_{x,z} = \frac{r_e \beta^*_{x,z}}{2\pi\gamma} \cdot \frac{N_2}{\sigma_{x,z} (\sigma_x + \sigma_z)} \]

Final limit:
1) emittance blowup,
2) lifetime reduction,
3) flip-flop effect

J. Seeman (1983)
Nonlinear beam–beam limit

\[
\xi_z = \frac{N_2 r_e \beta^*_z}{2\pi\gamma \sigma_z (\sigma_x + \sigma_z)} \approx \frac{r_e \beta^*_z}{2\pi\gamma \sigma_x} \cdot \frac{N_2}{\sigma_z}
\]

Typical dependence of specific luminosity on beam current

\[
L = \frac{N_1 n_b f_0 N_2}{4\pi \sigma_x \sigma_z}
\]

\[
L_{\text{spec}} = \frac{L}{N_1 N_2} = \frac{1}{N_1} \frac{n_b f_0 N_2}{4\pi \sigma_x \sigma_z}
\]

(VEPP-2M example)
Distribution deformation

LIFETRAC simulations example

DAFNE example: beam profile measurements.

Vertical profile significantly differs from Gaussian distribution.
Nonlinear beam-beam

6th order betatron resonances & synchro-betatron satellites

BB-interaction produces:
1) High-order resonance grid
2) Footprint, overlapping resonances

FMA: footprint

Resonances in normalized amplitudes plain

VEPP-4 simulations example (flat e⁺, e⁻ beams)
What can be done to increase significantly beam-beam parameter threshold?

Integrability should be implemented!

Half-integrability:
1) Round beams (+1 integral of motion >> 1D nonlinearity remains)
2) Crab-waist approach for large Piwinsky angle
3) Vicinity to half-integer resonance.

Even closer to full-integrable beam-beam?
1) Round beams + special longitudinal profile?
2) …?

Reduction of nonlinear motion dimensions number is very important: diffusion along stochastic layer through additional dimension is suppressed
Round beams at $e^+e^-$ collider

Luminosity increase scenario:

✓ Number of bunches (i.e. collision frequency)
✓ Bunch-by-bunch luminosity

$$L = \frac{\pi \gamma^2 \xi_x \xi_y \varepsilon_x f}{r_e \beta_y^*} \left(1 + \frac{\sigma_y}{\sigma_x}\right)^2$$

Round Beams:

$$L = \frac{4\pi \gamma^2 \xi^2 \varepsilon f}{r_e^2 \beta^*}$$

✓ Geometric factor:
✓ Beam-beam limit enhancement:
✓ IBS for low energy? Better life time!

$$(1 + \sigma_y / \sigma_x)^2 = 4$$
$$\xi \geq 0.1$$
The concept of Round Colliding Beams

Axial symmetry of counter beam force together with x-y symmetry of transfer matrix should provide additional integral of motion (angular momentum $M_z = x'y - xy'$). Particle dynamics remains nonlinear, but becomes 1D.

Lattice requirements:

• Head-on collisions!
• Small and equal $\beta$-functions at IP: $\beta_x = \beta_y$
• Equal beam emittances: $\varepsilon_x = \varepsilon_y$
• Equal fractional parts of betatron tunes: $\nu_x = \nu_y$

V.V. Danilov et al., EPAC’96, Barcelona, p.1149, (1996)
**Historic beam-beam simulations**

\[ \xi = \frac{N r_e \beta^*}{4 \pi \gamma (\sigma^*)^2} \]

“Weak-Strong”

I. Nesterenko, D. Shatilov, E. Simonov, in Proc. of Mini-Workshop on “Round beams and related concepts in beam dynamics”, Fermilab, December 5-6, 1996.

“Strong-Strong”

Beam size and luminosity vs. the nominal beam-beam parameter (A. Valishev, E. Perevedentsev, K. Ohmi, PAC’2003)
VEPP-2000 main design parameters @ 1 GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>24.388 m</td>
</tr>
<tr>
<td>Energy range</td>
<td>150 ÷ 1000 MeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1</td>
</tr>
<tr>
<td>Number of particles</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Betatron tunes</td>
<td>4.1/2.1</td>
</tr>
<tr>
<td>Beta-functions @ IP</td>
<td>8.5 cm</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1 \times 10^{32}$ cm^{-2}s^{-1}$</td>
</tr>
</tbody>
</table>

13 T final focusing solenoids

max. production rate: $2 \times 10^7$ e^+ s

BEP, 800 MeV booster
Beam size measurement by CCD cameras

3m11
25.12 18:21:01
x=317.1 y=208.0
a=31.9 h=31.0 p=22.3
U=9164 ph=2104
Max=1.1714 (1)
I=0.14 (0/1)

1m1r
25.12 18:18:53
x=376.2 y=232.0
a=25.1 h=83.5 p=88.8
U=29561 ph=3724
Max=32949 (1)
I=0.55 (0/4)

1m2l
25.12 18:19:00
x=304.6 y=269.4
a=25.7 h=99.6 p=68.7
U=7891 ph=2946
Max=10973 (1)
I=0.14 (0/1)

2m2l
25.12 18:19:24
x=221.2 y=135.16
a=22.0 h=42.2 p=36.1
U=21548 ph=2208
Max=24389 (1)
I=0.14 (0/1)
Round Beams Options for VEPP-2000

Round beam due to coupling resonance? The simplest practical solution!

Both simulations and experimental tests showed insufficient dynamic aperture for regular work in circular modes options.

Flat to Round or Mobius change needs polarity switch in solenoids and new orbit correction.
Machine tuning

1) Orbit correction & minimization of steerers currents using ORM techniques ($\delta x, y < 0.5\text{mm}$)
2) Lattice correction with help of ORM analysis ($\delta \beta < 5\%$)
3) Betatron coupling in arcs ($\delta \nu_{\text{min}} \sim 0.001$)
4) Working point small shift below diagonal

Specific luminosity & linear lattice correction

After correction

Before correction

After correction

Before correction

Lifetrac by D. Shatilov, 2008
Simulations for $E = 500$ MeV. 50 mA corresponds to $\xi \sim 0.1$.

Invariance of beam sizes @ IP is the essential VEPP-2000 lattice feature.
Dynamic sizes at the beam-size monitors

\[ \xi_{\text{nom}} \sim 0.12 \]
Fixed lattice energy scaling law: $L \propto \gamma^4$

Peak luminosity overestimate for “optimal” lattice variation

$\beta^* \propto \gamma$, $L \propto \gamma^2$

Obtained by CMD-3 detector luminosity, averaged over 10% of best runs

Energy ramping
e$^+$ deficit
Beam-beam effects
DA, IBS lifetime
"Flip-flop" effect

E = 240 MeV, $I_{\text{beam}} \sim 5 \times 5$ mA

Pickup spectrum of the coherent oscillations

Coherent beam-beam $\pi$-mode interaction with machine nonlinear resonances?
Beam-beam parameter extracted from luminosity monitor data

Coherent oscillations spectrum

BB-threshold improvement with beam lengthening:

\[ \Delta \nu = \arccos(\cos(\pi \nu_0)) - 2\pi \xi \sin(\pi \nu_0) \bigg/ \pi - \nu_0 \]

\[ \Delta \nu = 0.175 \rightarrow \xi = 0.125/\text{IP} \]

\[ \xi_{\text{nom}} = \frac{N \beta_{\text{nom}}}{4\pi\sigma^2_{\text{nom}}} \]

\[ \xi_{\text{lumi}} = \frac{N \beta_{\text{nom}}}{4\pi\sigma^2_{\text{lumi}}} \]

E = 392.5 MeV

\( U_{\text{rf}} = 35 \text{ kV (purple)} \)

\( U_{\text{rf}} = 17 \text{ kV (blue)} \)
Bunch lengthening: microwave inst.

Bunch length measurement with phi-dissector as a function of single beam current for different RF voltage @ 478 MeV.

Energy spread dependence, restored from beam transverse profile measurements.
Proper profile of longitudinal distribution together with $\Delta \psi = n\pi$ betatron phase advance between IPs makes the Hamiltonian time-independent, i.e. integral of motion.

$$\rho(s) \propto \frac{1}{\beta(s)} \quad \beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

Synchrotron motion should prevent full integrability(?)

$$\beta^* = 5\text{cm} \quad \sigma_s = 5\text{cm} \quad \xi = 0.15$$

D. Shatilov, A. Valishev, NaPAC’13

Beam-beam resonances suppression due to hour-glass effect(?)

Beam sizes data analysis @ 392.5 MeV

Note: bunch lengthening is current-dependent...

\[ U_{RF} = 35 \text{ kV} \]

\[ I = 15 \text{ mA corresponds to } \xi \sim 0.1 \]
1. $\text{e}^+, \text{e}^-$ beams from new BINP Injection Complex (IC).
   - high intensity
   - higher energy (400 MeV);
   - high quality (!);

2. Booster BEP upgrade to 1 GeV.

3. Transfer channels BEP – VEPP to 1 GeV.

4. VEPP-2000 ring modifications.
Summary

- Round beams give a serious luminosity enhancement.
- The achieved beam-beam parameter value at middle energies amounts to $\xi \sim 0.1-0.12$ during regular operation.
- “Long” bunch ($\sigma_l \sim \beta^*$) mitigates the beam-beam interaction restrictions, probably affecting on flip-flop effect.
- VEPP-2000 is taking data with two detectors across the wide energy range of 160–1000 MeV with a luminosity value two to five times higher than that achieved by its predecessor, VEPP-2M. Total luminosity integral collected by both detectors is about 110 pb$^{-1}$.
- Injection chain of VEPP-2000 complex was upgraded and commissioned. Achieved $e^+$ stacking rate is 10 times higher than formerly.
- During upcoming new run we intend to achieve the target luminosity and start it’s delivery to detectors with an ultimate goal to deliver at least 1 fb$^{-1}$.
Backup slides
Beam-beam parameter evolution

537.5 MeV, June-2011
0.07

\[ \xi_{\text{nom}} = \frac{N^r e \beta_{\text{nom}}^*}{4\pi \gamma \sigma_{\text{nom}}^2} \]

392.5 MeV, June-2013

511.5 MeV, May-2013
0.08

\[ \xi_{\text{lumi}} = \frac{N^r e \beta_{\text{nom}}^*}{4\pi \gamma \sigma_{\text{lumi}}^2} \]

0.09 (purple points)
**LIFETRAC predictions**

1. Very high $\xi$ threshold values for ideal linear machine lattice, $\xi_{th} \sim 0.25$.

2. Chromatic sextupoles affect significantly on bb-effects decreasing threshold down to $\xi_{th} \sim 0.15$. (Break of the angular momentum conservation by nonlinear fields asymmetric to x-y motion)

3. Working point shift from coupling resonance under diagonal ($v_x > v_z$) preferable than vise versa. (Emittances parity breaking.)

4. Uncompensated solenoids acceptable in wide range ($\delta v_{x,z} \sim 0.02$) while coupling in arcs provided by skew-quadrupole fields should be avoided. (Angular momentum conservation break by skew-quads, breaking x-y symmetry of transport matrix.)

5. Inequality of x-y beta-functions in IP within 10 % tolerance does not affect on bb-effects.


7. Beam lifetime improves with working point approach to the integer resonance.

Qualitative agreement of all predictions with experimental experience.
Luminosity measurement via beam sizes @ CCD cameras

SND and CMD-3 luminosity monitors:
1) Slow (1 measurement ~ 1/2 minute)
2) Large statistical jitter at low beams intensities

\[
L = \frac{f_0 \cdot N^+ \cdot N^-}{4\pi \cdot \sigma^*^2} \quad \Rightarrow \quad L = \frac{f_0 \cdot N^+ \cdot N^-}{4\pi \cdot \sqrt{(\sigma_x^+)^2 + (\sigma_x^-)^2)(\sigma_z^+)^2 + (\sigma_z^-)^2}}
\]

Needed:
1) Beams current measurement \(e^+, e^-\) (ФЭУ)
2) 4 beam sizes \(\sigma^*\) (with current dependent dynamic \(\beta^*\) and emittance) ⟷ reconstruction from 16 beam profile monitors.

Assumptions:
1) Lattice model well known (transport matrices)
2) Focusing distortion concentrated within IP vicinity.
3) Beam profile preserve **Gaussian distribution**.

\[
\beta_x^+, \beta_z^+, \beta_x^-, \beta_z^-, \varepsilon_x^+, \varepsilon_z^+, \varepsilon_x^-, \varepsilon_z^- \quad 2 \times 4 = 8 \text{ parameters} \quad / \quad 8 \times 2 \times 2 = 32 \text{ measured values.}
\]
Luminosity monitor

\[ L = 8.477 \times 10^{30} \pm 1.37 \times 10^{30} = 30.52 \text{ nbn}^{-1}/\text{hour} \]

VEPP-2000 Luminosity (\(10^{30} \text{cm}^{-2} \text{s}^{-1}\)) Fri 9 Mar 2012 08:30:52

800 MeV

\[ L = 9.806 \times 10^{28} \pm 2.77 \times 10^{28} = 0.35 \text{ nbn}^{-1}/\text{hour} \]

VEPP-2000 Luminosity (\(10^{30} \text{cm}^{-2} \text{s}^{-1}\)) Thu 4 Apr 2013 22:35:01

180 MeV
Extracted from luminosity beam size @ IP
High order resonances

Weak-strong tune scan of threshold counter beam current value.

Single positron beam lifetime as a function of betatron tune.
20mA @ 500MeV
Intrabeam scattering and DA

Single beam emittance growth with beam current, $E=220$ MeV

Calculated in simple model
DA dependence with $\beta^*$ variation. $\nu=0.128$, $E=1$ GeV