Recent beam-beam effects at VEPP-4M & VEPP-2000

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ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders
Perimeter: 366 m
Energy range: 1 ÷ 5.5 GeV
Number of bunches: 2×2
Betatron tunes: \( \beta_x^*, \beta_z^*, \eta^* \)
\( \xi_x / \xi_y \): 75/5/80 cm
Luminosity @ 1.85 GeV: \( 2.3 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1} \)
VEPP-4M luminosity

\[ L \sim E^4 \]

\[ \xi_Y \]

\[ I, mA \]

\[ E, MeV \]

\[ L, 10^{28} \text{ cm}^{-2}\text{s}^{-1} \]
VEPP-2000
Motivation of the round beam use in e+e- collider

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

_round beams:

\[ L = \frac{\pi \gamma^2 \xi_x \xi_y \epsilon_x \epsilon_f}{r_e^2 \beta_y^*} \left(1 + \frac{\sigma_y}{\sigma_x}\right)^2 \]

_round beams:

\[ L = \frac{4\pi \gamma^2 \xi^2 \epsilon \epsilon_f}{r_e^2 \beta^*} \]

- **Geometric factor:**
  \[ \left(1 + \frac{\sigma_y}{\sigma_x}\right)^2 = 4 \]

- **Beam-beam limit enhancement:**
  \[ \xi \geq 0.1 \]

- **IBS for low energy? Better life time!**
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.

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

V.V. Danilov et al., EPAC’96, Barcelona, p.1149, (1996)
“Weak-Strong” Beam-Beam Simulations

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

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-Beam Simulations

Beam size and luminosity vs. the nominal beam-beam parameter (A. Valishev, E. Perevedentsev, K. Ohmi, PAC’2003)
VEPP-2000 layout & parameters

Main parameters @ 1GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>24.388 m</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>200 ÷ 1000 MeV</td>
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</tr>
<tr>
<td>Number of bunches</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Number of particles</td>
<td>1×10^{11}</td>
<td></td>
</tr>
<tr>
<td>Betatron tunes</td>
<td>4.1/2.1</td>
<td></td>
</tr>
<tr>
<td>Beta-functions @ IP</td>
<td>8.5 cm</td>
<td></td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>1×10^{32} cm^{-2}s^{-1}</td>
<td></td>
</tr>
</tbody>
</table>
Lattice functions of half of the ring

VEPP-2000 lattice special feature: $\beta^*$ variation modifies radiative beam emittance in the way that $\beta^* \varepsilon = \sigma^2 = \text{inv} (\beta^*)$
Beam size measurement by CCD cameras
Round Beams Options for VEPP-2000

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

Flat to Round or Mobius change needs polarity switch in solenoids and new orbit correction.
Working points for different options

“Flat”

“Normal Round”

“Single möbius”

“Double möbius”

“Flat” & “Normal round”

“Single möbius”

“Double möbius”
Arguments in favor of work on a coupling resonance

Advantages of (+- +-) option as compared to the “basic mode” (++ --):
1) Easy switch to flat beams
2) Better sextupole solution, wider dynamic aperture

Disadvantages not yet known
Luminosity scaling approach

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

\[ \sigma^* = \varepsilon \beta^* = \text{inv}(\beta^*) \]
Dynamic beta, emittance and size

Calcs for $E = 500$ MeV. 50mA corresponds to $\xi \sim 0.1$
For VEPP-2000 optics, the dynamic beta and emittance compensate, sizes @IP = const
Dynamic sizes at the beam-size monitors

\[ \xi_{\text{nom}} \approx 0.12 \]
Luminosity measurement via beam sizes @ CCD cameras

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

$L = \frac{f_0 \cdot N^+ \cdot N^-}{4\pi \cdot \sqrt{(\sigma_x^+)^2 + (\sigma_x^-)^2)(\sigma_z^+)^2 + (\sigma_z^-)^2}}$
Luminosity vs. beam energy

DA & IBS lifetime
“Flip-flop”
Lack of positrons
ramping

2010-2011 run, 2011-2012 run, 2012-2013 run
Beam current vs. energy

![Graph showing beam current vs. energy](image-url)
Nominal beam-beam parameter

\[ \xi_{\text{nom}} = \frac{N^{-} r_{e} \beta_{\text{nom}}^{*}}{4 \pi \gamma \sigma_{\text{nom}}^{*2}} = \frac{N^{-} r_{e}}{4 \pi \gamma \varepsilon_{\text{nom}}} \]
Beam size growth @ IP

- 720 MeV
- 537.5 MeV
- 320 MeV
- 250 MeV
Luminosity & “real” bb-parameter

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

\[ \xi_{\text{nom}} = \frac{N^r e \beta_{\text{nom}}^*}{4\pi \gamma \sigma_{\text{nom}}^*} \]
"Flip-flop" effect

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

Coherent beam-beam \pi\text{-mode interaction with machine nonlinear resonances?}
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
Summary

• «Round beams» – not a bad idea!
• Maximum luminosity achieved: $1 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ at $\varphi$-meson energy in 2008 run and $2.5 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ at $E=850 \text{MeV}$ in 2012.
• Potentially $2 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ possible at $\varphi$ and $1.6 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ at 2 GeV.
• More positrons required! VEPP-5 injection complex will supply them in near future.
• The weak-strong simulation clearly predicts better lifetime for lower tunes. Dynamic aperture enhancement required to move working point lower as well as to squeeze $\beta^*$ at low energy.
Weak-strong simulations

Deformation of the weak beam distribution is in question.
The simulation model for D. Shatilov’s “Lifetrac” code:

1) 2-period lattice with the chromaticity correction sextupoles,
synchrotron oscillations, longitudinal slicing
2) Whatever variations, $E = 509$ MeV and constant $\beta^* = 5$ cm,
   $\sigma_z = 17$mm, emittances $\sim 46 – 48$ nm
3) Tracking for $10^4$ damping times ($t_{x,y} \sim 350,000$ turns $\sim 28$ ms)
4) Arc is tracked by P. Piminov’s code “Acceleraticum”, i.e. the natural
   chromaticity is correctly simulated, sextupoles (and other
   machine nonlinearities) can be included. Comparison with
   the previous “no sextupole” option is available.
Things to be avoided in round colliding beam operation (1)

Detuning from the coupling resonance

\[(v_1 + v_2)/2 = 0.10\]

Detuned by +0.01

20 mA

30 mA

40 mA

50 mA
Things to be avoided in round colliding beam operation (2)

Detuning from the coupling resonance

On resonance

Detuned by –0.01
Things to be avoided in round colliding beam operation (3)

Large non-compensation of the solenoidal field

\[ \pm 0.01 \]

\[ \pm 0.005 \]

Different tune separation caused by solenoids
Things to be avoided in round colliding beam operation (4)

Non-round beta-functions @IP

\[ \beta_x = \beta_y = \pm 5 \text{cm} \]

\[ \beta_{x,y} = (5 \pm 0.5) \text{cm} \]

Difference in \( \beta_x, \beta_y \) means the angular momentum non-conservation
Things to be avoided in round colliding beam operation (5)

x-y coupling in the arcs

Tune separation 0.005

x-y coupling in the arcs also gives the angular momentum non-conservation
Tune scan along the diagonal

...reveals almost constant specific luminosity!
Namely, \( L = 1 \times 10^{28} \text{ cm}^{-2} \text{s}^{-1} \text{mA}^{-2} \)
Only the beam tails expand at higher tunes and cause limitation of the beam lifetime

Lifetime @ 50mA, s

![Graph of lifetime vs. \((v1 + v2)/2\)]
@50mA, with sextupoles: tune dependence of the tails

\[(v_1+v_2)/2\]
@50mA, without sextupoles: very weak beam-beam effect

$(v_1 + v_2)/2$
The beam-beam parameter varied:

Conditions:
arc tunes separation $A_x/2$ by the doublet (D3,F3) & F1 lenses, beta$^*$x,y kept equal; circular modes and a wider tune split produced by twist 0.79kGs*66.5524cm: $Q_x = 4.1115$, $Q_y = 2.0893$,
alpha = 0.036, $Q_s = 0.0028$, beta$^*$ = 4.5cm
bunch length: 1.74cm (50kV RF), $dE/E_0 = 3.5e-04$
emittances: $E_x = 8.464e-06$, $E_y = 3.065e-06$ cm*rad
decrements: $d_x = 1.905e-06$, $d_y = 1.998e-06$, $d_e = 4.318e-06$ (per 1/2 turn)