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Report on Mini-Workshop on "Round Beams and Related Concepts in Beam Dynamics"

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The Mini-Workshop on "Round Beams and Related Topics in Beam Dynamics" was held from December 5 to 6, 1996, at Fermilab. About twenty people from Cornell, Budker INP(Novosibirsk), Fermilab, University of Colorado (Boulder), ANL, and University of Michigan (Ann Arbor) attended. Plenary session presentations were as follow:

Dave Finley	Fermilab	Opening address
Slava Danilov	Novosibirsk	Round Colliding Beams for Increasing Luminosity
Richard Talman	Cornell	Mobius Modification of CESR
Yaroslav Derbenev	U.Mich.	Hollow Beams Concept
Vladimir Shiltsev	Fermilab	Tevatron Round Beams Simulations
Yuri Shatunov	Novosibirsk	Around Round Beams in Novosibirsk
Elizabeth Young	Cornell	Round Beam Results at CESR
Igor Nesterenko	Novosibirsk	Beam-Beam Effects Simulations for VEPP-2M with Flat and Round Beams
John Cary	U.Colorado	4D Simplectic Maps with Reduced Chaos
Slava Danilov	Novosibirsk	Integrable Optics Concept

As it was originally supposed, a lot of discussions arose during the presentations, so, each of nine talks took almost an hour, while the entire Workshop took one and a half days.

In his opening address, Dave Finley expressed an interest of proton machines community in "round beams" schemes which had being widely discussed for a long time as a way to increase beam-beam tune shift and, therefore, luminosity of colliders. Thorough evaluation of the "round beams" for the Tevatron upgrade has become a pressing problem since the experimental proof of principle at CESR.

1 "Round" Beams and Other Concepts: Theory, Simulations, Experiment

Slava Danilov made theoretical overview of the "round beams" (RB) concept. Three essential condition of the beams are:

1. equal horizontal and vertical emittances $\epsilon_x = \epsilon_y = \epsilon$;
2. equal beta-functions at interaction point (IP) $\beta_x^* = \beta_y^* = \beta$;
3. equal betatron tunes $\nu_x = \nu_y = \nu$.

Due to the symmetry, beam-beam tune shifts ξ are the same in both planes, that means valuable enhancement in luminosity of $e^+ - e^-$ colliders. Then, there is an additional integral of motion – angular momentum $\mathcal{M} = x \cdot y' - y \cdot x'$, and its conservation reduces 2D dynamics to one (radial) degree of freedom and, therefore, to a 1-dimensional set of resonances. All that improves beam stability and reduces particles diffusion under the impact of non-linear forces of the opposing beam. The most effective improvement needs the tune ν to be close to integer or half-integer. A general form of linear transformation matrices which conserve $\mathcal{M}$ is found to be a superposition of turns in betatron phase space (equal for both x and y) and in physical spaces.

Danilov also demonstrated several models with further elimination of stochasticity by maintenance of an additional integral of motion. The most remarkable case appears when the longitudinal bunch charge distribution $\rho(s)$ becomes inversely proportional to the beta-function at the IP: $\rho(2s) = Const/\beta(s) = Const/(\beta^* + s^2/\beta^*)$. Under such circumstances the impact of the counter round beam ceases to depend on time in normalized variables; that also helps to prevent diffusion.

The presentation of Richard Talman was devoted to modification of the CESR $e^+ - e^-$ collider for RB operation with use of Mobius optics. The Mobius accelerator can be obtained from a "normal" one by simple insertion of several skew quadrupoles which change polarization of betatron oscillations accordingly to $(x, x') \rightarrow (y, y')$ and $(y, y') \rightarrow (-x, -x')$. As in usual optics, certain matching of the Twiss parameters β and α is necessary. As the result of such a "twist", original ring tunes (ν_x, ν_y) yield Mobius tunes $\nu_{1,2} = (\nu_x + \nu_y)/2 \pm 1/4$ for "rotating" normal modes (note, that frequencies of signal spectra measured at either horizontal or vertical pick-ups are the same); and fluctuations of synchrotron radiation contribute equally to vertical and horizontal emittances $\epsilon_x^{Mobius} = \epsilon_y^{Mobius} = \frac{1}{2}\epsilon_x^{no-Mobius}$. An advantage of the obtained round beams is that higher ξ_{max} are possible, so, the CESR specific luminosity $\mathcal{L}/I_{tot} \propto \frac{\xi_{max}}{\beta_y^*}(1 + R)/2$ can be increased about 2.5 times after the modification (present parameters set of ξ_{max}^y=0.04, β_y^*=1.8 cm, $R \approx 0$ to be changed to ξ_{max}=0.1, β^*=3.6 cm, R=1). Another advantage is the possibility to control the ring chromaticity with substantially improved sextupole distribution, since in Mobius lattice each of them affects both planes.

Numerical simulations for CESR-Mobius were made in "strong-strong" regime with self-consistent transverse distribution which was found to be close to "near-Rayleigh" distribution $dN(r)/dr \propto r \exp -(r/\sigma)^p/2$ where the parameter p is somewhat different from 2. Simulated luminosity, size blow-up and halo population have pointed to optimum tune points (twice-around tune)/2=0.77 or 0.27. The projected maximum luminosity of CESR with round beams is above $2 \cdot 10^{33}\ s^{-1} sm^{-2}$, that assumes installation of the Mobius section at North area (to be completed in spring 1997), more bunches per beam (from 9 to 15), and superconducting quads in South interaction region.

Vladimir Shiltsev presented simulations of beam-beam effects with RBs in the Tevatron $p\bar{p}$ collider. Hadron beam emittance formation is affected by space-charge and intrabeam scattering effects rather than by synchrotron radiation, and usually horizontal and vertical emittances of the beams coming from injectors are almost equal. Because of that, there were considered not only Mobius lattice with $\pi/2$ rotation, but also two other schemes of the RB preparation: one of them assumes two opposite twists back and forth around the ring $x \to y \to x$, another does not use any $x-y$ coupling elements at all (usual uncoupled lattice). Of course, different optics yield different resonant frequencies, e.g. 2-D resonances merge into 1-D ones when coupling increases from 0 to Mobius twist. Numerical comparison shows that all three round beam schemes provide larger luminosities and slower particle diffusion rates than a "non-round" collider where all three RB conditions are broken. All schemes were found to be rather stable to slight variation of emittance and tune ratio from 1 – at least over 10^5 turns of "weak-strong" tracking that corresponds to about 2 sec in Tevatron. A scan over tune ν (the only tune for RB) with different rms bunch length σ_z allows to conclude an existence of two optimums in the length corresponding to smaller maximum betatron amplitude achieved by any macroparticle – one occurs when σ_z is somewhat smaller than β^*, another $\sigma_z \approx \sqrt{2}\beta^*$ – in a good accordance with Danilov's prediction.

Nevertheless, studies of the effects of various imperfections and errors suggest that proton RB dynamics is not favorable to coupling. In particular, the RB scheme without any coupling has shown somewhat better performance in luminosity and stability under conditions of non-zero residual dispersion, finite beam-beam separation and crossing angle at the interaction point, as well as for betatron phase advance asymmetry between two IPs. However, no studies have been done to answer other important questions for the Tevatron, namely, what scheme is the most stable with respect to numerous parasitic crossings (where beams are not round), and residual coupling and substantial nonlinearities along the ring.

Yaroslav Derbenev outlined the general concept of RB as a way to integrability of particle motion. His theoretical analysis also proves the angular momentum conservation in circular optics and suggests to choose working point about sum resonance $\nu_x + \nu_y = integer$. Proposal of further increase of luminosity is based on idea of "hollow (in phase space) beams" which are characterized by large amplitude of betatron oscillations a $(x, y = a_{x,y} \cos \Psi_{x,y})$, spread of amplitudes Δa is small, and emittance remains the same as for round beams (in normalized variables $\epsilon \equiv \pi a_0^2 = 2\pi a \Delta a$). In the result, at the interaction point such beams can be "superfocused" and the luminosity enhancement is proportional to $\propto a/\Delta a$. Another advantage of the "hollow beams" is $\Delta a/a$ times reduction of tune shifts due to the parasitic crossings at the rest of collider ring. A method to obtain the "hollow beams" is proposed.

The hit of the Workshop was talk of Elizabeth Young on a just finished successful test of the "round beams" idea at CESR. Resonant coupling method was used in order to obtain the RB instead of Moibius or other strong-coupled techniques. Weak $x-y$ coupling due to existing skew quadrupoles around IP was enhanced by merging horizontal and vertical natural frequencies $\Delta\nu_x = \Delta\nu_y = 0.77$. Particle motion "sloshes" between x and y every 100 turns or so, and as the result, beams are approximately "round". Some technical difficulties were overcome with off-energy injection, and finally collisions took place with up to some 20 mA current in each beam (one bunch per beam, no crossing angle) that yielded in luminosity about $\sim 10^{31}\ s^{-1}cm^{-2}$ with $\beta^*_x = \beta^*_y = 30$ cm. No drastic degradation of the beam lifetime occurred during the experiment.

The maximum achieved split of σ and π mode frequencies was about 38.1 kHz that is almost 0.1$\times$(CESR revolution frequency). Based on Yokoya-Koiso theory of coherent beam-beam modes one gets that corresponding maximum beam-beam parameter is $\xi_{max} = 0.075$ – in a good agreement with the value calculated from measured beam sizes. Besides the tune shift measurements, there were carried out extensive studies of the RB blow-up in "weak-strong" and "strong-strong" regimes with different currents and tunes from 0.76 to 0.83.

Two speakers from Novosibirsk – Yuri Shatunov and Igor Nesterenko – shed light on status of "round beams" at Budker Institute of Nuclear Physics. Experimental plans are now focused on modification of existing VEPP-2M $e^+ - e^-$ collider (0.5-1.4 GeV c.m.) to RB operation with use of four 8.6 T superconducting solenoids. Resulting coupling depends on field directions in each of the four, and both Mobius and "back-and-forth" schemes can be realized. Installation of solenoids and the first test are scheduled to fall of 1997 with goal to overcome the achieved up-to-date ultimate beam-beam tune shift (vertical) of $\Delta\nu_y \approx 0.13$.

Extensive simulation of RB for VEPP-2M and for ϕ-Factory which is currently under construction in Novosibirsk show that maximum beam lifetime occurs when momentum compaction factor α is negative. It was also found that at high currents when the beam-beam tune shift exceeds 0.1, the field of chromaticity correction sextupoles leads to substantial degradation of the beam. Longitudinal component of the beam-beam kick leads to particle energy variation at IP $\Delta E = Ne^2\beta'(s)/(2\beta(s)) \approx Ne^2 \cdot s/\beta^{*2}$ which can be comparable with cavity voltage (especially at low energy colliders). "Weak-strong" simulation code was tested with flat beams and rather good agreement with experimental results was observed.

2 Methods to Improve Dynamic Aperture

Two presentations were made regarding methods to control and reduce chaos, and to maximize dynamic aperture.

John Cary presented results of finding symplectic maps with reduced chaos. It was shown that in the case of $1\frac{1}{2}$ degrees of freedom, such maps can be easier selected with use of Greene's residues. Algorithm is as follow: for a map $z' = T(z)$, one has to find fixed points $z_0 = T^q(z_0)$ (both stable and unstable), then for linearized motion about these points $\delta z' \equiv z' - z = M(\delta z)$ the Greene's residue must be calculated $R \equiv [2 - Tr(M)]/4$. Residue R greater than $1/4$ in magnitude implies chaos that should be avoided by variation of the parameters of the map $T(z)$. A test was made for real lattice of the Advanced Light Source, the dynamic aperture of which was more than doubled with properly chosen several additional moderate strength octupoles and decapoles in each of periodic cells.

In $2\frac{1}{2}$ degrees of freedom the stability of fixed points is governed by 2 parameters: $A \equiv Tr(M)$ and $B \equiv Tr(M)^2 - Tr(M^2)$. An application to the ALS predicts possible 3.5-fold increase of xy volume available for stable beam operation, although it again requires numerous nonlinear magnets.

The final talk made by Slava Danilov was devoted to another approach to the integrable systems. Based on analytical calculations, he finds general forms of the perturbation kicks $F(x)$ which lead to additional integrals of motion $I(x,p)$ in some specific form, e.g. $I(x,p)$ is quadratic in momentum p, cubic, etc. If really existing linear and sextupole force is close to Taylor expansion of one of the integrable systems, then making minor addition of higher order fields one can transform previously chaotic map to everywhere stable one.

One of "integrable" solution for the "round beams" near 1/4 resonance is $F(r) = a \cdot r/(b + r^2)$ where a and b are arbitrary constants – that is rather close to the kick due to beam beam interaction, and if there is a way to vary charge distribution in counter bunch so that its force is close to $F(r)$, then one can qualitatively improve particles stability.

There was also shown an example of 2D accelerator integrable accelerator map with drift and thin lenses with stationary magnetic fields which can be considered as a prototype of real "integrable" accelerator.

3 Discussion

Numerous discussions at the Workshop covered many issues of round and integrable beams: ways to obtain the RB, details of simulation codes used for RB studies, planning of experimental study of the crossing angle effect at CESR, etc. The last scheduled session was devoted to practical implementation of the "round beams" at Fermilab. It was pointed out by FNAL scientists that the Tevatron is probably not the best machine for a proof of principle test because of technical difficulties. Instead of that, 8-GeV antiproton recycler ring has enough space for necessary $x - y$ coupling insertions and RB interaction region optics and with two intensive p and $\bar{p}$ beams. Further evaluation of the idea is under way.

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