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## FUTURE PROSPECTS OF COLLIDING-BEAM ACCELERATORS

C. Pellegrini

Laboratori Nazionali del CNEN, Frascati

The exercise of sitting at his own desk and trying to think to the possibility of development of any field of human activity is always stimulating. One of its first results is to realize how incomplete is our knowledge of that field and how many more informations would be needed to make reliable projections into the future.

The usual way out of this situation is to show one's personal degree of optimism in making some more or less reasonable extrapolations or in filling the holes in those cases when our ignorance is greater.

The field of colliding-beam accelerators is no exception to this rule and the same is true for my behaviour. So it is probably a necessary warning to tell you that I am defined by the majority of my friends as an optimist.

I have tried to obtain some evidence that I am not alone in this category and as a proof of this I can show you Table I, where a list is given of the colliding-beam storage rings now operating or under construction together with their expected performances

We could add to this list three other machines which are being designed at Brookhaven (Isabelle) and by a joint SLAC-LBL group (PEP), although their construction might be quite a few years away from now. These are:

		Beam energy	Luminosity
ISABELLE	p-p	200 GeV	$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
PEP	$\left\{ \begin{array}{l} e^+ - e^- \\ e^- - p \end{array} \right.$	15 GeV	$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
		15 - 65 GeV	$10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

Of all these machines the first five are now in operation and the numbers quoted for them are measured numbers. Comparing these four machines with those under construction or in the planning stages one notices an increase in beam energy and an increase in luminosity. While there is no doubt that the first can be achieved, the increase in luminosity requires some comments.

Consider for example the case of electron-positron storage rings. The luminosity can be written as

$$(1) \quad \mathcal{L} = f k \frac{N^2}{A}$$

where  $f$  is the revolution frequency,  $K$  the number of bunches per beam,  $N$  the number of particles per bunch assumed equal in the two beam,  $A$  the transverse beam area.

We know that the main effect which limits the luminosity is the beam-beam interaction. This limits the particle density which can be achieved in the beams at the crossing point without destroying the beams. This limit is usually written as (1)

$$(2) \quad \frac{r_e N \beta}{\gamma A} \lesssim \Delta v$$

where  $r_e$  is the classical electron radius,  $N$  the number of particles per bunch,  $\gamma$  is the particle energy in units of rest mass energy,  $A$  the beam transverse area,  $\beta$  the wavelength of

TABLE I - COLLIDING-BEAM STORAGE RINGS IN OPERATION OR CONSTRUCTION

Storage rings	Colliding particles	Maximum energy per beam in GeV	Luminosity in $\text{cm}^{-2} \text{s}^{-1}$	Beginning of operation	Comments
VEPP II	$e^+ - e^-$	0.7	$10^{28}$	1964	Single ring, one experimental section
ACO	$e^+ - e^-$	0.5	$5 \times 10^{28}$	1965	Single ring, one experimental section
ADONE	$e^+ - e^-$	1.5	$5 \times 10^{29}$	1969	Single ring, four experimental sections
ISR	$p - p$	28	$10^{30}$	1971	Double concentric rings, with eight crossing points
CEA	$e^+ - e^-$	3.5	$2 \times 10^{28}$	1971	Collisions take place in a by-pass of the CEA synchrotron
VEPP III	$e^+ - e^-$	3.5	$10^{31}$	1972	Single ring, with two experimental sections. Quoted luminosity is the design goal; the machine is still being tested.
VAPP IV	$p - p^-$	23	$10^{31}$	construction	Will use electron cooling to increase the density of the antiproton beam
SPEAR	$e^+ - e^-$	2.5	$10^{32}$	1972	Single ring, two experimental sections. Quoted luminosity is the design goal. The machine is being tested.
Doris	$e^+ - e^-$	3	$10^{33}$	construction	Two rings, vertically superimposed Two experimental sections
DCI	$e^+ - e^-$	1.8	$10^{32}$	"	Two rings vertically superimposed with four circulating beams.

betatron oscillations at the interaction point, and  $\Delta v$  is a constant of the order of  $2 \times 10^{-2}$ .

Other effects can limit the number of particles. For instance at high energies  $N$  is limited by the amount of radio-frequency power,  $P_\gamma$ , available to compensate the synchrotron radiation energy losses

$$(3) \quad 2fNU = P_\gamma$$

where  $U = \frac{4}{3} \pi \gamma^4 mc^2 \frac{r_e}{\rho}$  is the energy loss per turn. From (1), (2), (3) we obtain for the luminosity the formula

$$(4) \quad \mathcal{L} = \frac{3}{8\pi} \Delta v \frac{k\rho}{\beta} \frac{P_\gamma}{m_e c^2 \gamma^3 r_e^2}$$

which can be assumed to be valid, under the most usual conditions of operations, also for e-p collisions. At low energies one can be limited by the beam area  $A$ , which cannot be increased beyond a certain value. In this case

$$(5) \quad N = \frac{\gamma \Delta v}{r_e \beta} A$$

and

$$(6) \quad \mathcal{L} = kf \left( \frac{\Delta v}{r_e} \right)^2 \gamma^2 \frac{A}{\beta^2}$$

Since the beam area  $A$ , as determined by synchrotron radiation, scales with energy as  $\gamma^2$  we obtain in this last case that the luminosity increases as  $\gamma^4$ .

From (4) and (6) it follows that if we plot  $\mathcal{L}$  versus  $\gamma$  we obtain a graph of the type shown in Fig. 1, where  $\gamma_s$  is

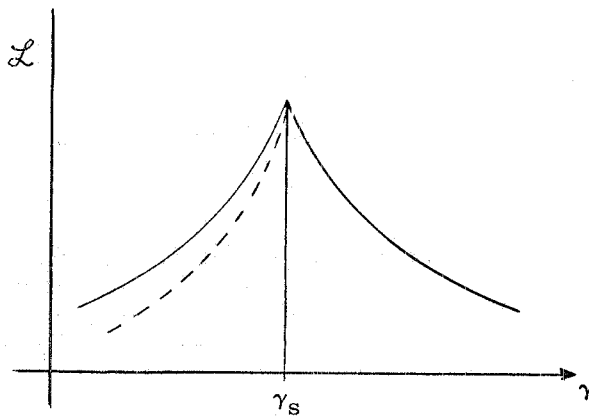


FIG. 1

the value of  $\gamma$  where the amount of stored current starts to be limited by RF power. The result of this is that for any storage ring one can obtain high luminosity values only in a limited energy interval.

The situation becomes more complicated when one considers that measurements done on Adone and ACO have shown that, in the formula for the density limitation due to beam-beam interaction,  $\Delta v$  is not a constant but, at least in a certain energy interval, it changes with energy like  $\gamma^{1.5}$  (2). One should also notice that we do not understand this fact, and this means that we do not understand the effect which puts the strongest limit on luminosity. Because of this energy dependence of  $\Delta v$ , the luminosity will change, for energy below  $\gamma_s$ , as  $\gamma^7$ . It seems also reasonable to assume that there is another critical energy,  $\gamma_c$ , such that for  $\gamma > \gamma_c$ ,  $\Delta v$  becomes again  $\gamma$  independent, but also this parameter is not known at the moment. It follows that the energy interval over which the quoted luminosity values will be obtained, is not well known.

Another remark which can be made is that to obtain the high luminosity values quoted in table I, one makes use of the  $\beta$  dependence of  $\mathcal{L}$ . Since  $\mathcal{L} \propto 1/\beta$  the reduction of  $\beta$  by a factor of about  $10^2$  below the normal values used in VEPP II, Adone, ACO and ISR, explains the greater luminosity values of the new machines. What happens in practice to the luminosity when  $\beta$  is reduced by a factor of  $10^2$  is still not completely known. Both ACO and Adone are being modified to investigate this point by reducing  $\beta$  by a factor between 2 and 10. The validity of the law  $\mathcal{L} \sim 1/\beta$  will be fully investigated, down to very small  $\beta$ -values, by SPEAR, which is now starting to operate. It is however important at this point to mention that the low- $\beta$  technique is not the only possibility to improve  $\mathcal{L}$  and that other options are also available.

At last I would like to mention that other limitations on the stored current and current density can be introduced by coherent beam instabilities. Although these can, in principle, be overcome by proper machine design or by using appropriate control systems, they can in practice introduce a limitation, or, at least, require costly and complicated control techniques.

Let me try now to draw some conclusions:

- a) From the existing programs and ideas it seems possible that in some years from now a number of colliding-beam storage rings will exist, offering to the experimental physicist the possibility of studying p-p reactions up to 400 GeV c. of m. energy, e-p reactions up to 65 GeV, and  $e^+e^-$  in the range 1 to 30 GeV.
- b) To obtain the required luminosity might require some new development and a better understanding of the physics of colliding beams; however, there is no reason, at present, to believe that these high luminosity values will not be reached.
- c) To obtain high luminosity over a wide energy interval we will probably need several storage rings with different characteristics.

The last point worth of mention is the possibility offered by the large proton synchrotron, like the NAL synchrotron and the CERN SPS, to obtain very high c. of m. energy for e-p collisions in a relatively inexpensive way. The idea is to have a small (say 5 GeV) electron storage rings having a common straight section with the large P S.

The c. of m. energy would be of the order of

$$E \approx 2 \sqrt{5 \cdot 400} \approx 90 \text{ GeV}$$

Assuming to observe e-p reactions only during the machine flat-top the luminosity is given by

$$\mathcal{L} = f k \frac{N_p N_e}{A} d$$

where d is the duty cycle. Assuming the parameters given for SPS and that one uses a  $\beta$  value of  $5 \times 10^{-2}$  m for the electron beam and 1 m for the proton beam it seems possible, in theory, to obtain a luminosity of  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ , with  $10^{13}$  electrons and  $10^{13}$  protons (3). One can notice that the proton beam could still be used for fast extraction, and 400 GeV proton physics, at the end of the flat top.

Finally I would like to mention that the possibility exists of some new developments, which might become important in the future although they are rather obscure at present. One of these is the possibility of obtaining unstable particle collisions, like  $\pi - \pi$ , K-K,  $\mu - \mu$ . It seems conceivable that, making use of the large particle fluxes from the meson factories and, perhaps, of very high magnetic fields, one could build a storage and collision system which would allow the study of unstable particle reactions. Some proposals in this directions have already been made<sup>(4)(5)</sup>.

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