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COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

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Summary

The present status of colliding beam devices is reviewed, and the limitations on their performance are discussed. Recent modifications to the design of the Stanford electron position storage ring are also discussed.

Status of Colliding Beams

The field of colliding-beam physics was born in 1958 with the start of construction of the first colliding-beam device by a Princeton-Stanford collaboration. This device, a 2 × 550 MeV electron-electron storage ring, yielded its first results on electron-electron scattering in 1963 and has since been dismantled. However, it spawned a host of more powerful offspring in Western Europe, the USSR, and here in the U. S. The widespread interest in these colliding-beam devices is of course due to the new kinds of phenomena they can study in particle physics and to the enormous center-of-mass energies they can reach at much less cost than conventional accelerators (a 2 × 3 GeV electron ring is equivalent in center-of-mass energy to a 36,000 GeV accelerator beam hitting a stationary electron target; a 2 × 28 GeV proton ring like the ISR at CERN is equivalent to an 1800 GeV proton beam hitting a liquid hydrogen target; a 2 × 400 GeV proton ring which could be built at NAL is equivalent to a 340,000 GeV proton beam on a hydrogen target).

Table I shows a list of those storage ring projects which are now working or under construction, together with their maximum center-of-mass energies, the year of their first operation, and their relative luminosities (reaction rate/unit cross section/unit time). These relative luminosities are given with respect to the Frascati project which is the highest energy ring now operating, and are not meant to be precise numbers but rather to show clearly the remarkable progress in the field. The first two projects were begun before the beam instabilities discovered at the Princeton-Stanford project were understood, and might be called first-generation machines. The next two electron projects were designed with a better understanding of these instabilities, and these second-generation machines achieved an increase in luminosity of roughly one to two orders of magnitude. The last three electron projects are third-generation machines which were designed after the invention of the "low-beta" technique by Robinson and Voss,[1] and are designed to have still another increase of one to two orders of magnitude in luminosity. It is worth noting also that the center-of-mass energies of the electron rings are roughly equivalent to the available reaction energies of the existing Brookhaven or CERN proton synchrotrons. This is not a meaningless comparison, since the greatest interest in the new electron rings lies in the strong interaction physics they can do.

Table I

Storage Ring Projects Now Operational or Under Construction

Location	Maximum total energy (2 beams)	Year of first operation	Relative luminosity
	ELECTRON RINGS		
Novosibirsk	1.4	1966	1/20
Orsay	1.1	1967	1/20
Frascati	3.0	1969	1
Novosibirsk	7.0	1971	10
CEA	7.0	1971	100
SLAC	6.0	1972	500
DESY	7.0	1974	1000
	PROTON RINGS		
CERN (p-p)	56	1971	20
Novosibirsk (p-$\bar{p}$)	46	1972	5

The proton rings listed do not have the luminosity of the third-generation electron machines both because they cannot take advantage of radiation damping to compress phase space, and because they have not yet made use of the low-beta technique (modifications to these devices to insert low-beta sections at a later time are possible). However, their center-of-mass energies are nearly a factor of two higher than that of the NAL machine operating at 500 GeV, and their reaction rates are equivalent to that of a secondary-particle beam at Brookhaven or CERN interacting with a liquid hydrogen target.

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

The rapid increase in design luminosity of more than four orders of magnitude in the less than 10 years since the Princeton-Stanford ring began operations is the consequence of a great informal international collaboration by many physicists in understanding the dynamics of circulating beams and the ecology of accelerators.

The behavior of beams in storage rings is now much better understood than in the days when machines like the CERN and Brookhaven synchrotrons were designed. While each new storage ring seems to find some new manifestation of the beam-environment interaction, the time required to understand and fix these problems has become very short.

One effect now limits the performance of storage rings and that effect is what is known as the incoherent beam-beam instability. There is a limit to the charge densities of two colliding beams above which some kind of apparently incoherent increase in the amplitude of betatron motion takes place. This growth in beam cross section above the limiting current density is surely driven by the highly non-linear forces involved in the collision of two gaussianly distributed beams. While the effect is not really well understood, the work of Courant[2] based on the early experience with the Princeton-Stanford ring resulted in an expression for the limiting current density which has withstood the test of time and of experiments at three other storage rings of quite different design.

We can all look forward in the next few years to an outpouring of experiments from both the electron and proton storage rings which will illuminate some of the darkest corners of hadron physics. Some of my theorist friends

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measure the worth of an experiment by the number of theoretical papers produced per experiment. With this measure, my prophecy is already fulfilled by Frascati where preliminary conference reports on the first experiments have begun to fill the literature with theoretical papers attempting to explain the results.

The Stanford Project — SPEAR

In August, 1970 we began the fabrication of a high energy, high intensity electron-positron storage ring at SLAC. The design of the present project has evolved over more years than I can contemplate with any real equanimity. Preliminary design work on a 3 GeV e^+e^- ring began at SLAC in 1962 and resulted in a formal proposal to the AEC in 1964. This design called for a single, relatively large-aperture ring with multibunch e^+ and e^- beams traveling in the same vacuum chamber. In 1965, when Robinson and Voss invented the "low-beta" technique, the design was modified to incorporate two long low-beta insertions.[3] In early 1969 the design was changed again to two smaller-aperture rings with a large horizontal crossing angle which seemed to us to allow better control of beam instabilities. The initial maximum operating energy was reduced, as was the maximum beam current, in the interest of economy. The name SPEAR (Stanford Positron Electron Asymmetric Rings) came from this design. In late 1969 in the interest of further economy we decided initially to build only one of the two asymmetric rings which would operate in the so-called one-bunch mode, preserving the option of adding the second ring at a later date. The name SPEAR was still appropriate as an acronym. Finally, in 1970 after some relatively minor but messy problems turned up in handling two beams in a single asymmetric ring, the single ring became symmetric and SPEAR became a name rather than an acronym. The single ring is derived from the double-ring design and we can still add the second ring at a later date.

Many of the technical details of the present SPEAR design are given in previous reports on the double ring[4] and on the single asymmetric ring.[5] Here I will describe only the general features of the design and go into detail only on those things which are different from previous versions. In its initial configuration SPEAR will be limited to a maximum operating energy of between 2.5 and 3 GeV each beam by the radiofrequency voltage capability of the RF system which will be installed in the ring. The magnets of the ring, however, are designed to operate at energies of up to 4.5 GeV, and an increase in the initial maximum operating energy thus requires only an increase in the available RF voltage and in the magnet power.

Figure 1 is a schematic of the storage ring which is composed of 12 standard cells and the 2 long low-beta insertions. The short straight sections between the standard cells are each 3 m long and are used for injection, RF, beam monitoring, various controls, etc. The lattice incorporates a set of distributed sextupole magnets to control chromatic aberrations of the ring. These chromatic aberrations are much larger than is normal in synchrotrons because of the very strong quadrupoles near the interaction region, which make the small beta. The total chromatic aberrations of the ring with the low-beta insertions are about 3 times what they would be if the low-beta sections were absent, and if uncorrected would prevent us from injecting the full ±1/2 percent energy spread which we plan to use.

Injection is by a standard beam bump and septum system. The transverse phase acceptance of the ring is sufficiently large to contain the entire phase space of the positron beam delivered from the Stanford Linear Accelerator. Injection will take place at an energy of 1-1/2 GeV and the ring will then be cycled to whatever energy is required for the physics experiments.

The ring will operate in the so-called one-bunch mode wherein a single circulating bunch of electrons and a single bunch of positrons will collide with near zero crossing angle only at the low-beta regions. This mode of operation ensures that no beam-beam interactions will take place at any point in the orbit other than that designed to control the two-beam incoherent instability. Electric plates are located in the vacuum chamber near the interaction regions to allow the variation of the beam crossing angle from zero to a maximum of roughly 2 milliradians.

The limiting luminosity of SPEAR as with other storage rings is determined by the incoherent two-beam instability. As I mentioned previously, this instability limits the current density in the beams in a manner which depends on the guide field parameters β_x and β_y and the beam energy. Figure 2 shows the design luminosity vs. energy of SPEAR. The maximum luminosity is 10^{32} cm^{-2} s^{-1} at an energy of 2 GeV each beam. At energies above 2 GeV the circulating beam current is limited by the available RF power and is proportional to E^{-4}. Control of the transverse dimensions of the beam to maintain the limiting current density set by the incoherent limit results in a luminosity proportional to E^{-3}. Below 2 GeV, the luminosity is limited by the aperture of the storage ring (the limiting aperture is outside the low-beta insertions). The beam current must be proportional to the beam energy if the limiting current density is not to be exceeded resulting in luminosity proportional to E^2.

The control of the beam cross-sectional area is not an easy task. The natural beam sizes determined by radiation damping give cross sections which are considerably smaller than those required to achieve the maximum luminosity of SPEAR. Other groups have increased the area of their beams by pulsing on a field which first induces coherent betatron oscillations and relying on the nonlinearities of the guide field to spread the phases of these betatron oscillations to fill the phase space. However, in a high-current storage ring like SPEAR a fast feedback system is essential for the control of single beam coherent oscillations, and the coherent motions induced by the above technique would saturate the kind of feedback system we require, rendering it ineffective. It appears possible to excite the beam without moving its center of charge by the use of a pulsed quadrupole field. This is technically difficult because of the very large frequency spread induced by the beam-beam interactions.

We have another option in SPEAR because of the design of the low-beta insertion. It is possible to use the momentum spread in the beam to control the horizontal size of the interaction point by varying the dispersion of the lattice at that point. The requisite vertical size can be obtained either by horizontal-vertical coupling of the betatron oscillations or by using a small vertical crossing angle. Figure 3 shows the beta (β) and momentum (η) functions of the storage ring in the region of the interaction point. The lower half of the figure shows the β and η functions when the lattice is set for zero dispersion, which is a condition used for injection. The upper half of the graph shows these functions when the dispersion at the interaction point is equal to 5 m which is the amount required to give the requisite horizontal size at an energy of 2 GeV. The matching of this high-eta setup to the rest of the ring requires the adjustment of one other quadrupole in the normal part of the lattice. The continuous change in dispersion from zero to the maximum without a corresponding change in the betatron tune requires the simultaneous adjustment of many magnet power supplies. This would be a difficult task for the human operator, but is a relatively simple job for the control computer which will run the storage ring.

The most difficult problem which most storage ring projects have faced in the early days of operation is the control of various kinds of instabilities. Besides the system of sextupole magnets to control chromatic aberrations and the feedback system to control single-beam coherent oscillations mentioned above, we plan also to install electric quadrupole lenses to split the betatron oscillation frequencies of the electron and positron beams, a special RF cavity to split the synchrotron frequencies of the two beams, and a set of octupole lenses to control the frequency spread in the beam in order to vary the strength of the Landau damping.

The fabrication of SPEAR is well along and on schedule. We plan to inject the first beam into the storage ring in April of 1972 and we think that we will be ready to begin high energy physics experiments around November of 1972.

References

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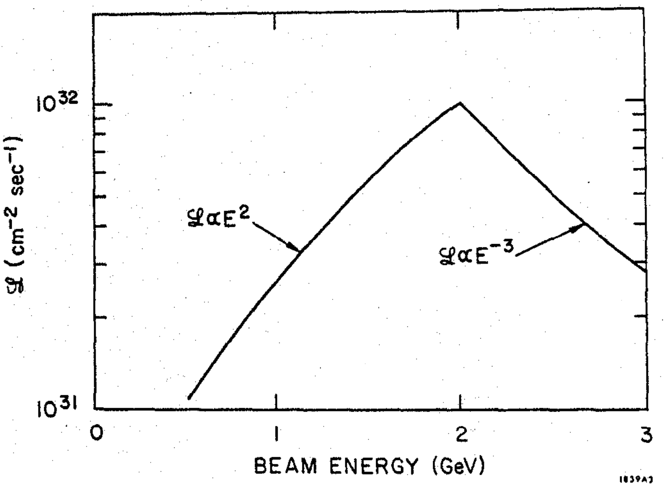

FIG. 2--Luminosity vs. energy.

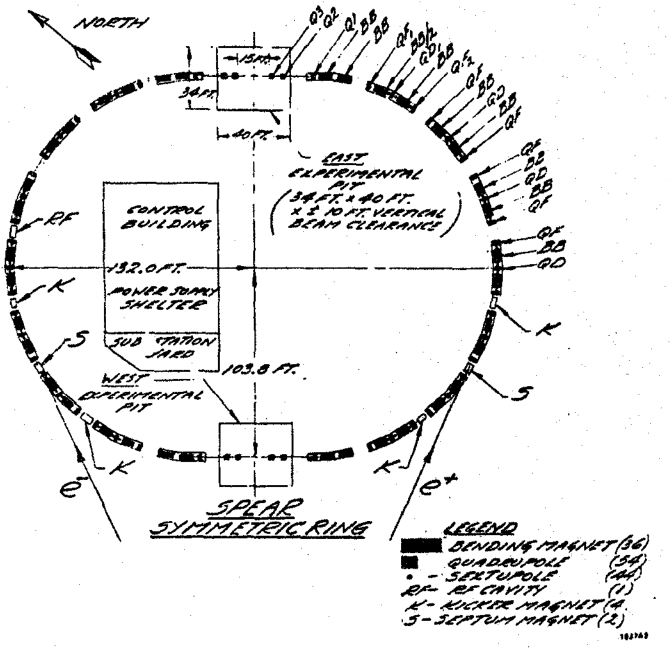

FIG. 1--Schematic of SPEAR.

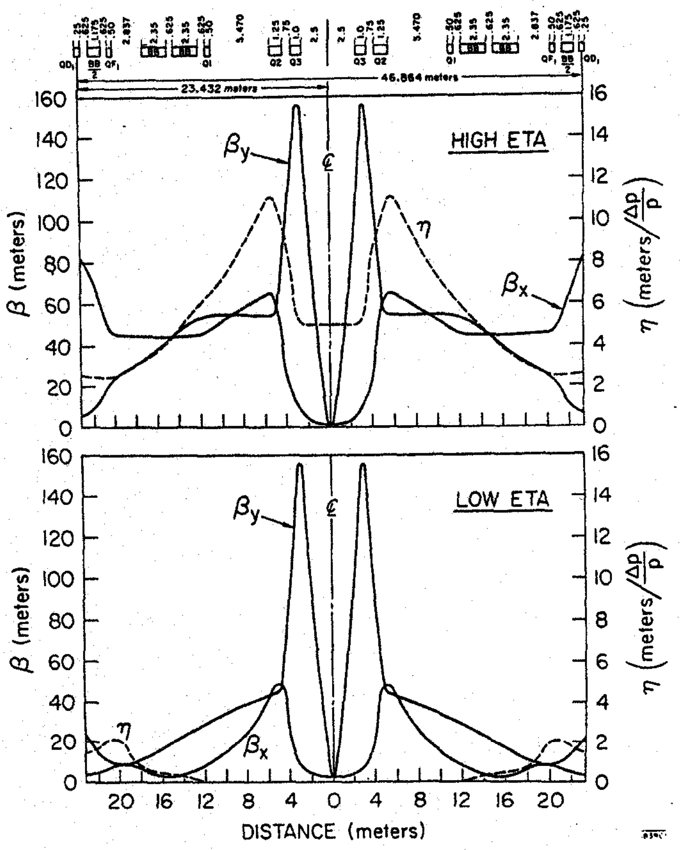

FIG. 3--Betatron functions and momentum function in the insertion for the high dispersion (upper graph) and zero dispersion (lower graph) modes of operation.