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OVERVIEW OF COLLIDING BEAM FACILITIES*

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I. INTRODUCTION

The high energy physics community worldwide is on the threshold of a great expansion in colliding beam facilities. The promising future that can be foreseen for the field is the result of a number of auspicious events. First, there are the breakthroughs that have been made in the technology of superconducting magnets, which have made it possible to envisage very large accelerators with energies in the hundreds of GeV; second, there are the recent experimental discoveries and theoretical advances that have been made in elementary particle physics, which suggest that new and significant elementary processes take place in this higher energy regime; and third, there is the continuing desire of society through its government agencies to support this fundamental research into the ultimate nature of matter.

An overall view of how these high energy facilities have progressed in recent years can be had by considering Fig. 1. Storage rings, utilizing two counter rotating interacting beams, are clearly the better choice for achieving higher center-of-mass energies. That this fact is recognized is evidenced by the increase in the number of colliding beam projects being constructed and proposed. Note the steeper slope for the storage ring lines which graphically expresses this idea.

Accompanying this trend in the direction of colliding beams is the need for reaching high luminosities. As can be seen from Fig. 2, the fixed target synchrotrons have mean luminosities about 4 to 5 orders of magnitude higher than storage rings. Unfortunately, increasing the useful or c.m. energy does not appear promising since the size of the synchrotron rises essentially as the square of the c.m. energy. Thus, the main thrust for future machines is in the colliding beam direction and the principal effort for performance gains is in reaching higher luminosities in colliding beam systems.

In section II, we describe the major high energy physics facilities around the world: those existing, those under construction and those being proposed. The emphasis here is on the nature and size of the facilities and on the major technologies required to support the worldwide high energy physics effort. In section III, we attempt to present a view of the beam collisions, describing briefly the instruments used to make the beams collide and those used to detect the products of particle interactions in the beam overlap region. Section IV is brief summary.

II. FACILITIES

In Table I we present a list of the major colliding beam facilities operating in the 1970's and those projected for the 1980's and

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1990's. One can see that the large and costly projects are either in the construction phase or in the design phase. The only existing proton-proton facility is the one kilometer circumference Intersecting Storage Ring (ISR) at CERN in Geneva. A schematic of the various machines on the CERN site, including the ISR, is shown in Fig. 3; while a picture of the Geneva area with the PS, ISR, and SPS machines superimposed is given in Fig. 4. In contrast to the number of pp colliding rings, there are in existence many electron-positron facilities, which were developed in the 1960's and early 1970's. The last of the "small" storage rings is SPEAR (Stanford Positron and Electron Accelerator Ring) at the Stanford Linear Accelerator Center (SLAC). Figure 5 is an aerial view of this facility with the 250 meter ring (SPEAR) on the lower right. The two mile long linear accelerator, which is used as the electron and positron injector can be seen, passing under the Freeway.

Fig. 1. Center-of-mass energy for high energy accelerators and storage rings over recent decades.

The first of the new storage rings to be available is the 2.3 kilometer PETRA ring at the DESY laboratory in Hamburg. This ring was completed in mid 1978 and became operational in October, 1978. A birdseye view of the DESY site is given in Fig. 6. In addition to the large PETRA ring circumscribing the site, one can also make out the smaller DORIS storage ring and, as well, the DESY synchrotron, the

Figure 3. Accelerator Complex at CERN.

Figure 4. Aerial View of the CERN Site.

Figure 5. Aerial View of the SLAC Facility.

Figure 6. Aerial View of the DESY Facility.

injector for both DORIS and PETRA. A photograph of the magnets in the PETRA tunnel is shown in Fig. 7. Here one can see the long dipoles (6 m), which produce the bending field for the circulating beams, and the shorter quadrupole magnets (2.5 m), which keep the beams focused in the transverse plane as they follow their long paths. The particles circulate on these paths for a few hours, a time corresponding to more than 10^{10} revolutions. It is to be noted that there is a single ring in the tunnel. This is an advantage for a machine in which oppositely charged particles collide: both beams can circulate in opposite directions in the same magnetic field. PEP, a project similar to PETRA, is scheduled for operation in early 1980 at SLAC (see figs. 5 and 8).

Fig. 2. Luminosity vs available energy for accelerator and storage rings.

Anticipation of possible experimental breakthroughs in very high energy electron-positron collisions has led to suggestions for the construction of even larger rings to accommodate electrons and positrons with energies of 100 GeV and even higher per beam. A specific proposal to build such a facility at CERN, to be called LEP (Large Electron Positron), has been made. Much discussion has taken place as to exactly what ring size is appropriate for the project. Figure 9 is a map of the Geneva area. Drawn on this map is the 20 kilometer long circumference of a LEP design. Such a machine would yield 70 GeV per beam and require a total power of 100 MW in order to supply the

Figure 7. Tunnel and Magnets of the PETRA Ring.

Figure 8. SLAC Site Showing PEP Facility.

Figure 9. Geneva Area Showing Proposed LEP Facility.

TABLE I. Storage Rings: Energy and Cost

Machine	ADONE (Frascati)	SPEAR (Stanford)	PETRA (Hamburg)	LEP (Geneva)	SPS (Geneva)	ISR (Geneva)	ISABELLE (Brookhaven)	VBA
Type of beam Collisions	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$p\bar{p}$	pp	pp	$pp, p\bar{p}$
Number of rings	1	1	1	1	1	2	2	2,1
Maximum energy (GeV) ^a	1 x 1	4 x 4	18 x 18	85 x 85	270 x 270	30 x 30	400 x 400	5000 x 5000
Maximum Luminosity (cm ⁻² sec ⁻¹)	10 ²⁹	10 ³¹	10 ^{32b}	10 ^{32b}	10 ^{30b}	10 ³¹	10 ^{33b}	10 ^{33b}
Time of Operation (typical year)	1970	1975	1979	1988	1982	1975	1986	1995
Size (km) (circumference)	0.1	0.25	2	30	7	1	4	25
Approximate Construction Cost	\$5 M	\$10 M	\$100 M	\$800 M	\$250 M +\$100 M	\$100 M	\$275 M	\$1 B
Others in this Category	ACO (Orsay)	DORIS (Hamburg)	PEP (Stanford)		FNAL (Chicago)			Super ISABELLE

^a1 GeV = 1.6×10^{-10} joule

^bEstimate

emitted synchrotron radiation. Klystrons are an efficient source of this rf power. An example of a klystron for the PEP storage ring is shown in Fig. 10. The energy is transferred to the beam via resonant cavities through which the beam passes. A straight section of the PEP ring with rf cavities is displayed in Fig. 11. To replace the large energy loss in LEP, more than 1.5 kilometers of active cavity length will be needed. It therefore appears that with the existing rf technology, LEP could well represent the limit in the construction of electron machines of the SPEAR type. This rf barrier is not a rigid one, and a promising technique on the horizon may be the introduction of superconducting cavities with the accompanying reduction in required rf power. Such an "improvement program" could raise the energy of LEP to approximately 110 GeV/beam. The hope at CERN is to have the first stage of LEP completed and operational by as early as 1988.

The recent advances in superconducting magnet technology have made possible the achievement of very high energies for proton beams. Proton-proton colliding beam facilities, and more recently proton-antiproton facilities, are under construction. After the successful operation of the ISR at CERN, a proposal was made by Brookhaven National Laboratory to construct a new facility for pp collisions with energies of up to 400 GeV per beam and maximum luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. The project, called ISABELLE, (ISA for Intersecting Storage Accelerator and "BELLE" for beautiful), is now in the construction phase. An artist's conception of the overall ISABELLE facility on the Brookhaven site is presented in Fig. 12. Figure 13 is a view of the tunnel cross section showing the superconducting magnet dewars of the two rings which are required to guide the two counterrotating, interlaced proton beams. These rings will cross, or intersect, at six regions along the circumference and thereby provide six areas for high energy experiments. The ISABELLE schedule calls for completion by 1986.

At CERN, a project has been initiated to construct a facility that collides proton and antiprotons using one of the existing accelerators on the site, the SPS (Super Proton Synchrotron), (see Figs. 3 and 4). As one can imagine, such a project will be difficult to bring into operation. Not only are there the practical problems involved in converting an existing facility and, at the same time, minimizing the interference with an on going experimental program, but there is also the fundamental problem of accumulating enough antiprotons which are needed to carry out reasonable experiments. To obtain a source of antiprotons one bombards a heavy target with high energy protons and collects the antiprotons at some lower energy. In rough figures, to obtain 1 antiproton, 10^7 protons are needed. Thus, the antiproton accumulation must take a long time and the phase space of the beam must be continuously compressed. Difficult as this task appears, CERN has taken it on. A similar type of facility is under active consideration at the Fermi National Accelerator Laboratory (FNAL) near Chicago. Here, a new superconducting magnet ring is about to be installed in the 6.3 kilometer tunnel housing the 400 GeV accelerator. A panoramic view of the FNAL site is given in Fig. 14. Figure 15 is a view of the FNAL tunnel, showing some superconducting magnets installed underneath the

Figure 10. PEP Klystron Gallery

Figure 11. PEP RF Cavities.

Figure 12. ISABELLE Facility on Brookhaven Site

Figure 13. Storage Ring Tunnel for ISABELLE.

Figure 14. Panoramic View of Fermilab.

Figure 15. Main Ring Tunnel at Fermilab.

"Main Ring" magnets. Because of the higher magnetic field capability, and the lower overall power consumption of the superconducting magnets, the energy of the $p\bar{p}$ collisions at FNAL will be about four times higher than at the CERN $p\bar{p}$ project (2000 GeV in the center-of-mass compared to about 540 GeV).

III. COLLIDING BEAMS

There are two designs for colliding beam systems. The first is the single ring system which can be used in the case of short oppositely charged bunches circulating in opposite directions. As we have mentioned, because of the opposite charges, the same magnetic lattice will affect the counterrotating bunches identically. The bunches must be short in length so that they collide only in the specific regions where the experimental detector apparatus is located. Electron-positron colliding beam systems work in this way, and the $p\bar{p}$ facilities under development for the CERN SPS and for the FNAL superconducting ring also work in the same way. The second design is the one used at the ISR and also planned for ISABELLE. It consists of two counterrotating beams of the same charge contained in two separate, but interlaced, magnet systems. The beams move in parallel arcs for some distance, and at specified "interaction regions," they are bent toward each other and cross at an angle. This collision angle essentially determines the length of the "interaction diamond". After the collision, the beams diverge and again follow parallel paths, interchanged with respect to the center of the machine. Eight such crossings exist at the ISR, and six are planned for ISABELLE.

In Fig. 16 the electron-proton single ring collision design is schematically shown, with some magnitudes for the collision length ($\sim \frac{1}{2}$ the bunch length, since the bunches are moving at equal speeds in opposite directions) and the interaction cross section. Figure 17 is a photograph of the MK-II Solenoid detector at SPEAR. One can visualize the tiny bunches of particles entering the center of the detector from both sides, some electrons and positrons interacting, and producing secondary particles that spiral radially toward the outer cylinders of detectors. Superimposed on the photographs of the SPEAR facility in Fig. 18 are arrows which indicate how the electrons and positrons enter the ring and subsequently collide in specific areas.

The proton-antiproton systems that are being developed are similar in concept to the electron-positron setup. However, the magnitudes of the interaction length and the collision cross section are different. Figure 19 is a schematism for the collision geometry of this system.

A sketch of the geometry of $p\text{-}p$ collision is given in Fig. 20. The significant difference between these collisions and the $p\bar{p}$ ones, for example, is that the collision region has a diamond shape and its overall length is determined by the crossing angle. In addition, the ISR beams are not bunched, but rather they are continuous around the two rings. This is also the mode of operation presently planned for ISABELLE. It might be mentioned, though, that bunching in this latter case is an optional mode of operation which has no influence on the

Figure 17. Mark II Solenoid Detector at SPEAR.

Figure 18. Colliding e^+e^- Beams at SPEAR.

collision geometry. The point is that, for long bunches, the collision length does not depend on the bunch length. A view of the crossing region at the ISR (the split field magnet interaction region) is shown in Fig. 21, while Fig. 22 shows an artist's conceptual view of the lepton detector region proposed for ISABELLE. To be noted are some implications of the great difference in crossing angles in the two cases (at the ISR, the crossing angle is twenty-five times larger than at ISABELLE, ~ 250 mrad compared to 10 mrad): (1) the beam pipes remain close together in ISABELLE, requiring that the region close to the collision region remain free of magnets; and (2) the final ring separation is much larger at the ISR necessitating a much wider tunnel (~ 15 m tunnel diameter at the ISR compared to ~ 5 m at ISABELLE).

Fig. 16. Collision geometry for e^+e^- beams.

Fig. 19. Collision geometry for $p\bar{p}$ beams.

Fig. 20. Collision geometry for pp beams.

IV. SUMMARY

In summary, we give in Table II a complete list of the major high energy physics facilities, those that are operating, those under construction and those being proposed formally as national projects. Given are the different accelerators and storage rings that make up these facilities and the performance either obtained or anticipated. They are divided into world regions: facilities in the U.S., in Western Europe, in the Soviet Union, and in East Asia. It is apparent that the world physics community has embarked on an adventure of major proportions. This paper has attempted to give a glimpse into the construction and technologies that are needed to transform this vision into reality.

TABLE II.
LIST OF HEP FACILITIES

(A) Fixed Target (Protons)

Laboratory	Date of First Beam	Maximum Beam Energy (GeV)	Beam Intensity (Protons per Second)	Status
<u>U.S.</u>				
BNL, AGS	1960	28	8×10^{12}	Operating
ARGONNE, ZGS ^a	1963	12.5	2×10^{12}	Operating
FERMILAB, MAIN Ring	1972	400	3×10^{12}	Operating
FERMILAB, ENERGY SAVER	1981	500	1×10^{12}	Construction
FERMILAB, TEVATRON	1984	1000	1×10^{12}	Planned

Figure 21. Split-Field Intersection Region of the ISR.

Figure 22. Lepton Detector at the ISABELLE Facility.

TABLE II. (Continued)

Western Europe

CERN, PS	1959	26	8×10^{12}	Operating
CERN, SPS	1976	400	3×10^{12}	Operating

Soviet Union

DUBNA, JINR	1957	10	2×10^{10}	Operating
SERPUKHOV, IHEP	1967	76	4×10^{11}	Operating
MOSCOW, ITEP	1973	10		Operating
SERPUKHOV, UNK I	~ 1985	400	7×10^{12}	Construction ^b
SERPUKHOV, UNK II	?	3000	7×10^{12}	Planned

Others

JAPAN, KEK	1976	12	10^{12}	Operating
PRC, BEIJING	1985	50	2.5×10^{12}	Construction

^aThe ZGS has accelerated polarized protons. It ceased operation in October, 1979.

^bPersonal communication.

(B) Fixed Target (Electrons)

Laboratory	Date of First Beam	Maximum Beam Energy (GeV)	Beam Intensity (Electrons per second)	Status
<u>U.S.</u>				
SLAC, LINAC ^a	1966	31	2×10^{14}	Operating
CORNELL, SYNCHROTRON	1967	12	2×10^{11}	Operating
<u>Western Europe</u>				
DESY, SYNCHROTRON	1964	7.4	3×10^{13}	Operating
<u>Soviet Union</u>				
YEREVAN, ARUS	1967	6.1	5×10^{12}	Operating

^aUpgrading to 31 GeV from 22 GeV was accomplished in 1979.

TABLE II. (Continued)

(C) Colliding Beams (Electrons X Positrons)

Laboratory	Date of First Beam	Maximum Beam Energy (10^9 eV)	Luminosity (Events per cm^2 per second)	Status
<u>U.S.</u>				
SLAC, SPEAR	1972	4 x 4	10^{31}	Operating
CORNELL, CESR	1979	8 x 8	10^{32a}	Operating
SLAC, PEP	1979	15 x 15	10^{32}	Construction
<u>Western Europe</u>				
FRASCATI, ADONE	1969	1.5 x 1.5	10^{30}	Operating
DESY, DORIS	1974	5 x 5	10^{30}	Operating
ORSAY, DCI	1976	1.8 x 1.8	10^{31}	Operating
DESY, PETRA	1978	15 x 15	10^{32b}	Operating
DESY	1986	33 x 33	10^{32}	Planned
CERN, LEP	1988	85 x 85	10^{32}	Planned
<u>Soviet Union</u>				
NOVOSIBIRSK, VEPP3	1969	3.5 x 3.5		Operating
NOVOSIBIRSK, VEPP4	1979	7 x 7		Construction

^aCirculating beam just obtained--expected performance not yet achieved.

^bPETRA has achieved 17 GeV per beam. Its luminosity is presently about 1% of its projected value.

(D) Colliding Beams (Protons/Antiprotons)

Laboratory	Date of First Beam	Maximum Beam Energy (GeV)	Luminosity (Events per cm^2 per second)	Status
<u>U.S.</u>				
FERMILAB, TEVATRON(pp)	1983	1000 x 1000	10^{30}	Planned
BNL, ISABELLE (pp)	1986	400 x 400	10^{33}	Construction
<u>Western Europe</u>				
CERN, ISR pp	1971	31 x 31	2×10^{31}	Operating
CERN, SPS pp	1982	270 x 270	10^{30}	Construction

TABLE II. (Continued)

Soviet Union

SERPUKHOV, UNK pp	?	3000 x 3000	10^{30}	Planned
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Other

JAPAN, TRISTAN pp	?	100 x 100	10^{30}	Planned
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(E) Colliding Beams (Electrons x Protons)Western Europe

DESY	?	33(e ⁻) x 1000(p)	10^{30}	Planned
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Other

JAPAN, TRISTAN	?	20(e ⁻) x 300(p)	10^{30}	Planned
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