CESR II: A PROSPECTUS

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Introduction

A high luminosity collider for e^+e^- in the Z^0 region, CESR II, has been described previously in Cornell publications CLNS 80/456 and CLNS 81/492. A physical layout of the ring, showing its proportions is presented below. For reasons of symmetry and for achievement of full independence of IR's and acceleration sections, 8 straights are used, four for I.P.'s and four for the rf apparatus.

This accelerator is designed to minimize capital plus operating power costs. The capital cost, based on detailed calculations presented in the references will be 220M$ (1982) while the operating costs will be 35M$ per annum (1982).

In order to make possible the construction of such a high performance accelerator for that price, technological innovations have been incorporated into its design and our most advanced understanding of accelerator physics is applied to get the highest performance per dollar possible from the more conventional aspects of the design. In particular, 5000 cells of superconducting cavities are used to minimize the size of the ring and very tight focusing is used to make the beam as dense as possible, thus minimizing the rf power necessary for a given luminosity. In addition, full advantage of the heavy radiation damping is taken to maximize the luminosity.

This approach raises a number of technical issues: Will superconducting cavities work in storage ring environment for a long period of time? Will single beams of the necessary current be stable in the presence of such a high impedance cavity system? Can one tolerate a beam-beam interaction of the strength proposed? With such strong focusing, will the magnetic aperture be adequate to maintain the beam stable with long life?

Each of these issues has been addressed experimentally and, where appropriate, theoretically from first principles and phenomenologically by scaling from already operational accelerators. We believe that these investigations show that the design reflected in the parameter list is sound. In what follows, we summarize the substance and results of the investigations.

Accelerating System

As detailed in CLNS 80/456 and 81/492, we have developed a 1.5 GHz superconducting acceleration system based on sheet metal fabrication methods applied to the metal niobium. Two submodules, of 5 resonant cells each, were recently assembled together and tested successfully in the CESR storage ring. These cavities were fully equipped with automatic tuning and high power couplers and windows for 1.5 GHz power and strong couplers for the higher modes excited by the beam. In this test rf and refrigeration parameters were under feedback control as they will need to be in the full system. Operating at an accelerating gradient of 1.8 MV/m and Q of 10^9, the 10 cavity assembly was able to accelerate, stably, a 7 mA beam at 3.5 GeV with the normal CESR rf system on tune but unpowered. Operating together with the normal CESR system, the superconducting assembly accelerated up to 12 mA and enabled us to operate with bunch lengths in the range 27 picoseconds (rms) to over 300 ps. No beam-cavity interaction induced bunch lengthening or energy spread was observed and none was expected. Under these conditions the beam induced higher order mode power, about 500 watts, was successfully extracted without significant addition to the refrigeration load. The accelerating field limit during the test was due to heating around the mouth of one of the higher mode extractors. A subsequent design change in the extractor permitted a fully equipped sub-module to operate with a Q of 3×10^9 at 3 MV/m and 1.5×10^9 at 3.5 MV/m. These results and the results of a one-cavity, 500 MHz superconducting beam test recently completed successfully at DESY together with the long-term tests carried out with superconducting S-band cavities in the Cornell Synchrotron in 1974-75 in which gradients of 4 MV/m were maintained, show that there is no inherent incompatibility of microwave superconductivity and the storage ring environment and beam stability conditions. Indeed, the one-meter cryogenic assembly used in the CESR beam test, fitted with the improved cavities, could be multiplied 500 times to produce a workable CESR II rf system. Encouraged by these results, however, we believe that a considerably more economical system can be built by combining our sub-modules into larger assemblies and by increasing the operating field level which will be our immediate goal in the near future.

Single Beam Stability

Beam-environment interactions have often limited the current in accelerators. While we have learned to minimize that interaction over most of the circumference of circular accelerators and storage rings by working hard to make smooth vacuum chambers, the unavoidable beam-cavity interaction is quite strong. In accelerators such as CESR II and LEP the number of cavities will necessarily be very large because of the large energy losses per revolution due to synchrotron radiation.

Longitudinal or transverse instabilities due to the beam-cavity interaction can be of two general classes, the so-called resonant and broad band interactions. In the resonant interaction, changes in beam size and position, both longitudinal and transverse and corresponding changes in cavity fields build up over a number of revolutions with memory residing both in the cavity fields and in the beam. This process can be particularly strong if the resonant frequency of a particular cavity mode coincides with one of the natural beam frequencies, such as a particular sideband of the beam revolution frequency. Unwanted effects of this type of interaction can be avoided by feedback, by control of the accelerator optical parameters and, most importantly, by damping of the offending cavity modes so that beam generated fields die out between successive cavity passages. In the case of CESR II, these resonant interactions and their cure have been dealt with in the reports referred to above. Careful calculations and bench measurements, verified in the superconducting cavity beam test described briefly above, make us confident that the CESR II beam current will not be limited by these resonant effects. The broad band effects are of a different nature. Here, the instability driving fields in the cavities do not build up turn-by-turn but are the result of an almost local interaction between the beam particles and their own transient wake fields as they pass through the accelerating portion of the ring. These wake forces are the moving source analog of the image forces of electrostatics. In frequency language, the wake fields are the superposition of the fields of all of the modes of the cavities which can be driven by the beam. The literature on this subject is too large to be reviewed here. Suffice it to say that in the case of very long bunches, i.e., the bunches are longer than typical chamber dimensions, a rather good theoretical and experimental understanding has been achieved over years of hard work.[1,2] The problem can be attacked analytically by writing a nonlinear partial differential equation for the beam phase space distribution functions in terms of the beam spectra and impedance spectrum of the vacuum chamber. By use of clever mathematics and judicious approximations one can seek current thresholds at which the distribution functions begin to grow. Good results are obtained in cases where the overlap of beam and impedance spectra are not too broad.[1,2] This method has been extended to cases of shorter bunches where the overlap is considerably broader.[3-6] (There are many, many other useful references.) While these complex analytical methods have advanced greatly in recent times, experience with their use as engineering and ab initio predictive tools is very limited at this time. Fortunately, in very recent times, a new approach, that of computer simulation, has been developed.[7-11] High quality simulations have been made possible by the development of efficient computer codes for calculating the longitudinal and transverse cavity fields generated by arbitrary distributions of charge.[12-14] Starting from initial phase space distribution functions, the simulator works in a loop, computing the self-generated wake forces and the kicks they give the beam particles as they pass through the cavities. The simulator then tracks the beam particles around the accelerator taking focusing, damping and quantum fluctuation effects into account. At the entrance to the cavity chain the new distribution functions are computed and new wakes and forces are computed and the process repeated. In this way the evolution of the beam distribution functions can actually be observed and recorded and stability or instability can be determined. If the beam is stable, its energy spread and physical dimensions are determined and can be compared with the distributions that would obtain if no collective effects were present. While this "engineering science" is still very new, the results are most promising and the agreement with experiment is most gratifying. Most satisfying is that the simulation results manifest the very complex physical phenomena actually observed. Unfortunately, the microscopic details of the calculated distribution functions are largely inaccessible to the experimental verification at our present level of measurement capability. It is the envelopes of the distribution that we can see now and they agree rather well with the simulation. Some recent results of simulation calculations done at Cornell are presented in appendices to this report.

The results of this method as applied to CESR II are that, at 50 GeV, currents of more than twice those needed are stable and exhibit little bunch lengthening or spreading. At the 20 GeV planned injection energy the needed currents are stable if wigglers are used to enhance the rather small natural damping that obtains at that energy and the phase focusing is kept strong. Details are given in an appendix.

Beam-Beam Interaction

As is by now well documented, the nonlinear focusing (defocusing) effect of one colliding beam or another can, if strong enough, result in dilution of the effective density of the beams at the crossing. As a result the beams fill the accelerator aperture and further strengthening (more current) leads to reduced beam life and high backgrounds in the detectors. The physical details of this process are still a matter of hot debate. Some insights have been gained; in the case of electron machines, by use of computer simulations[15-17] and analytical approximations.[18] Recently phenomenological analyses[19,20] have shown a basic connection between the amount of synchrotron radiation damping and the allowed strength of the beam-beam interaction. Very briefly, at a damping decrement of 10^{-4} per bunch crossing, a beam crossing, a beam-beam tune shift of 0.03 is sustainable in machines with reasonable physical and dynamic apertures. The allowed tune shift saturates at 0.06 for decrements in excess of 10^{-3} per crossing. This same behavior is manifested by the simulation programs. In CESR II, with its extremely strong damping decrement of 5×10^{-3} per bunch crossing a beam-beam shift of 0.05 should be sustainable. The analysis shows that a vertical aperture almost equal to the horizontal aperture will be necessary to maintain good lifetime. Such an aperture is provided.

Lattice and Dynamic Aperture

In order to maintain a high beam density at high energy where the quantum fluctuation driving is very strong, it is necessary to provide rather tight focusing. This results in rather large chromatic aberrations which must be corrected to avoid a large class of the single beam "head-tail" instabilities. This correction is normally effected by the addition of sextupoles. When the linear lens focusing is strong, the sextupoles must also be strong to make the chromaticity correction. This addition of a nonlinear element to the confinement force has the unfortunate consequence that the volume of phase space corresponding to stable confinement becomes limited. It can easily turn out that this dynamic aperture is smaller than the physical aperture of the accelerator. No general analytical algorithm exists, as yet, for working backward from a needed phase space volume (aperture) to a specific combination of linear and nonlinear lenses required. Given a particular lens distribution, one can use a tracking program to estimate the resulting aperture. The reliability of these tracking programs is thought to be quite good under some circumstances[21], but we have little experience in using them for ab initio engineering design where dynamic aperture is a crucial parameter. Another approach is to use a phenomenological approach in which one uses the functional dependence of the dynamic aperture obtained from a simplified analytical approach and scales from existing accelerators. This method tends to yield aperture values smaller than those given by tracking by as much as a factor of two. In general, the dynamic aperture is improved by adding more lenses to an accelerator of a given circumference. For CESR II we have chosen to use the more conservative of the two methods for determining dynamic aperture. The resultant lattice has a betatron tune due to the arcs of 42 and a total tune of 62, allowing the betatron focusing parameter at the crossing points to be as small as 2 cm without making the dynamic aperture less than the physical aperture. The most efficient focusing arrangement is built up of combined function bending magnets with lumped sextupoles interspersed between the bends. An equivalent arrangement using uniform field bends with quadrupoles and sextupoles interspersed is shown below along with a table of lens strengths, lengths and other properties of the focusing lattice.

Conclusion

Further developments of the superconducting cavity hardware, now underway, are expected to make significant economies in the complete accelerator installation. Cavity assemblies having all the features and performance levels required for CESR II have been successfully demonstrated. Other aspects of the design have been worked out by scaling from operating accelerators where possible and by developing new design tools where necessary. The most fundamental design parameters originally posited for CESR II appear to be sound.

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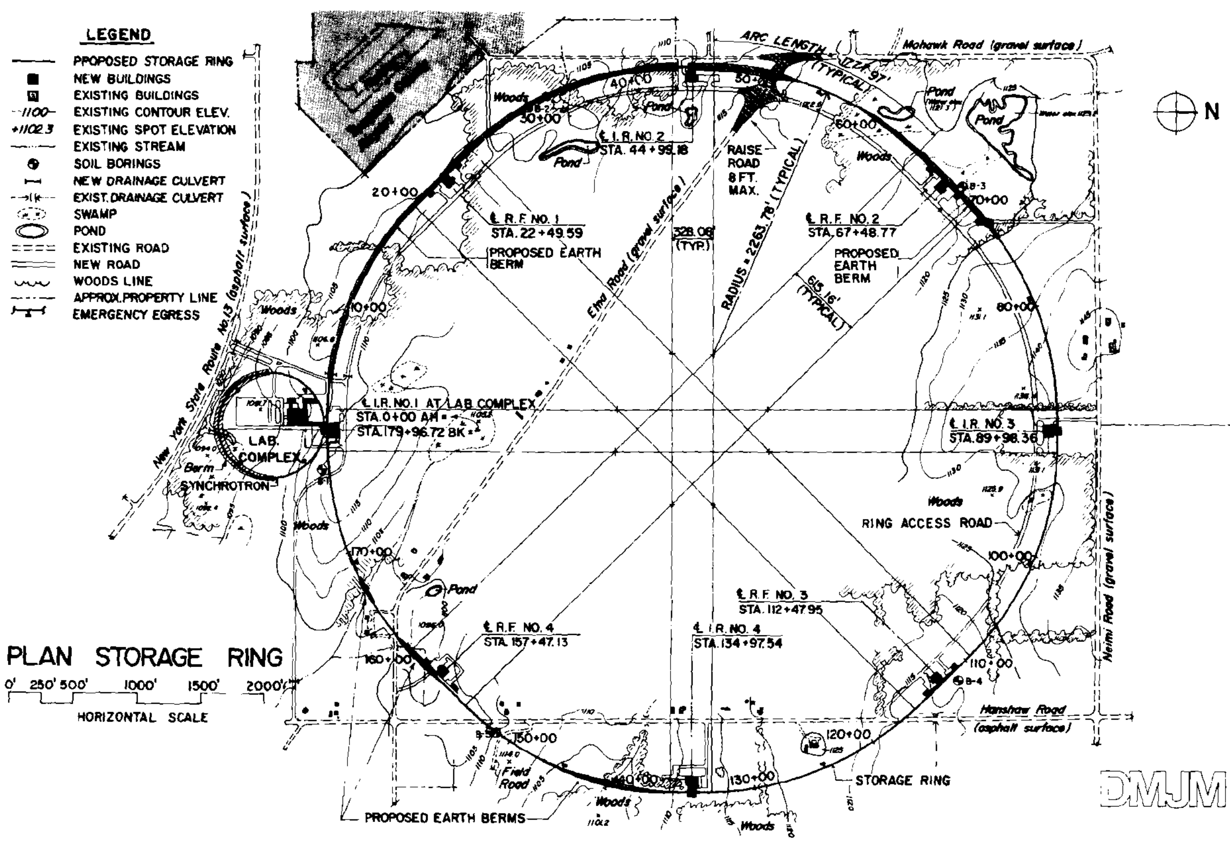

Parameter List

Nominal Peak Beam Energy	50 GeV
Max. Luminosity	$6\times10^{31}\,cm^{-2}sec^{-1}$
Number Of Interaction Points	4
Free Space For Experiments	$\geq 2m^{\dagger}$
Number Of Bunches Per Beam	2
Number Of Particles Per Bunch	2×10^{11}
Beam Current	3.5 mA
Circumference	5485m
Average Arc Radius	690 m
Aperture, Horiz. $(20\sigma_H+10\,mm)$	3.5cm
Aperture, Vert. $(50\sigma_V+10\,mm)$	2.8cm
Beam-Beam Tune Shift	0.05
Energy Loss Per Turn	2%
Beta Values At I.P. (H,V)	0.4, 0.03 m
Emittance (50 GeV)	$6.3\times10^{-8}m$

† For highest luminosity, space between IR Quads is 2m. For larger spacing, luminosity falls in proportion to the spacing.

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Injection Energy	20 GeV
Peak Beta In Arcs	24.2 m
Average Dispersion In Arcs	0.4 m
Betatron Tune (Total)	65
Betatron Tune (Arcs)	42
Phase Advance Per Cell	45°
Peak RF Voltage	1.5 GV
Synchrotron Radiation Power Total	7.7 MW
Cavity Radiation (Hour Power)	0.6 MW
RF Power (Total)	8.3 MW
RF Frequency	1500 MHz
Synchrotron Tune	0.14
Bunch Length, rms	4 mm
Energy Spread, rms	1.9×10^{-3}
Cavity Gradient	3 MV/m
Transverse Damping Time	1.7 m sec
Total Power For Facility	30 MW