CESR: PROJECTS AND PROSPECTS

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Summary

The accelerator program at the Cornell Electron Storage Ring (CESR) is focussed on increasing e^+e^- luminosity in the 10 GeV center-of-mass energy region of the Upsilon resonances. We have recently installed "micro-beta" inserts using permanent magnet quadrupoles, and are using a detailed computer simulation of CESR to study luminosity limitations related to the beam-beam interaction. We have also tested a low emittance lattice which is compatible with future operation of an undulator x-ray source. Research on superconducting RF cavities at Cornell is aimed at raising accelerating fields to a level at which superconducting RF could be an attractive option for TeV energy electron linacs.

Multibunch Operation

CESR normally operates with a saturated vertical beam-beam tune shift of .02 and with colliding beam currents limited by the beam-beam interaction to about 15 ma/bunch. It is possible to increase luminosity by adding bunches but collisions in the storage ring arcs must be prevented. This is done by horizontal electrostatic separators which send e^+ and e^- bunches on oppositely "pretzelled" orbits, giving typical separations of 2-3 cm at the crossing points in the arcs (Fig. 1). Machine operation is complicated by the closed orbits passing off center through sextupoles so that at least four families of sextupoles are required to maintain the focussing properties of the ring.

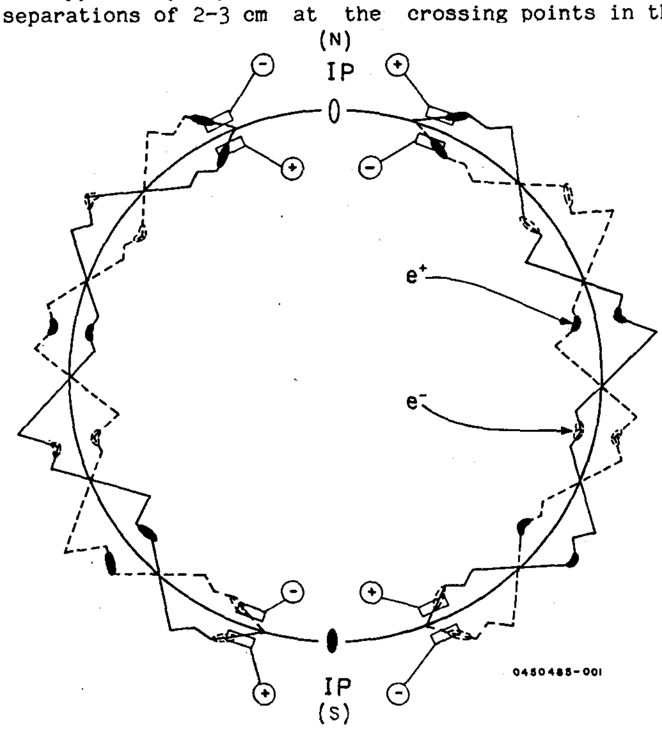

Fig. 1: e^+ and e^- orbits in guide-field arcs of CESR (not to scale). Encounter points for 7 x 7 bunches, at one time, are shown in black; bunches also meet at locations shown dotted.

We have now operated for several years with $3e^+ \times 3e^-$ bunches, giving peak luminosities of about 3×10^{31} $cm^{-2}sec^{-1}$, which is a factor of two improvement over single bunch operation. One problem is that with the electrons and positrons following different paths through the arcs, defects introducing coupling can affect the beams differently and result in misalignment at collision. A more fundamental limitation is the horizontal aperture available in our vacuum chamber (±45 mm in the arcs). We have found that the beam-beam interaction results in significant non-Gaussian tails on the horizontal beam profile, which in conjunction with the reduced horizontal aperture due to the pretzelled orbits and the perturbations at the crossing points in the arcs, reduce the beam lifetime for large bunch currents.[1] Our response has been to reduce the horizontal emittance of the beam which, however, also decreases the maximum stable bunch current compared to 1 x 1 operation.

In principle we can operate CESR with $7e^+ \times 7e^-$ bunches; in practice we have been limited to 3 x 3 by RF cavity problems which are mentioned below. Luminosity delivered during 1985 was about 150 pb^{-1}/IR.

Micro-Beta Insertion

Another possibility for increasing luminosity is to provide tighter focussing at the interaction points. For a storage ring operating with saturated vertical tune shift this should give $L \propto \beta_v^{*-1}$ since the smaller β_v^* decreases the beam height directly <u>and</u> through the smaller effect of the beam-beam kick. We have just finished installing, in CESR, a "micro-beta" insertion which should permit us to reduce β_v^* from 3 to 1.5 cm.

The additional focussing is provided by quadrupoles mounted inside the experimental detectors. Since they are exposed to the 10 kG axial field of the CLEO detector solenoid, iron quadrupoles are out of the question and we are using Rare Earth Cobalt (REC) permanent magnet quadrupoles based on the Co_5Sm magnet material.[2] This is possible because CESR operates over a narrow range of beam energies so that energy changes can be accomodated with one of our iron quadrupoles mounted just outside the REC quad.[3]

Properties of these quadrupoles are summarized in Table I and Figure 2 shows the schematic construction, which follows the prescription of Halbach[4] for assembling multipole magnets from REC magnet blocks. Actual assembly of the quadrupoles from the individual magnets is quite a feat, similar perhaps to assembling an iron quadrupole with its coils fully energized.

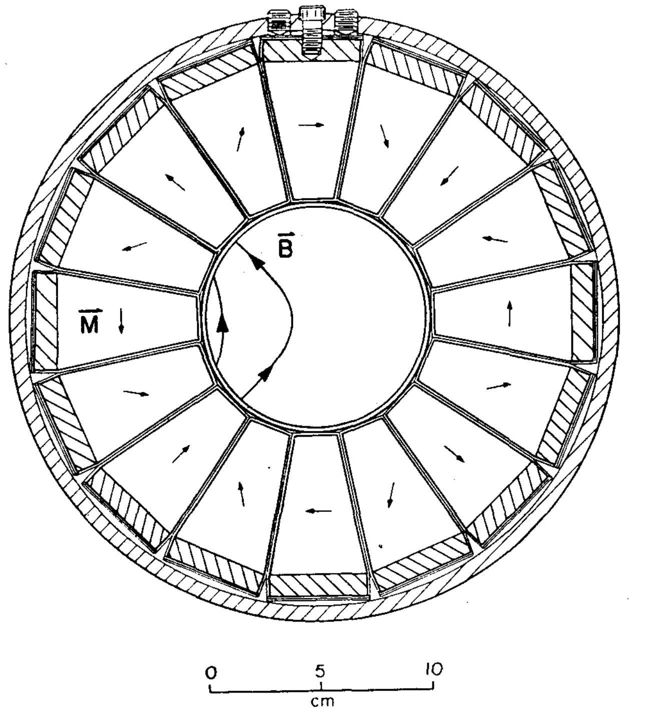

Fig. 2: Direction of magnetization M and magnetic field lines B in a 16 segment REC quadrupole

Table I

Properties of REC Quadrupoles

Bore	10.8 cm
O.D.	27.3 cm
Length	122 cm
Weight (Co_5Sm)	250 kg
Weight (Total)	450 kg
Gradient	15 T/m
Magnetic Permeability	1.03
Cost (Co_5Sm Only)	\$80 K

The REC quadrupoles resemble superconducting magnets in that the field depends entirely on the distribution of the magnetic moment source, with no shaped iron for smoothing. In general the blocks of Co_5Sm differ from each other at the several percent level, which leads to unacceptably high content of unwanted multipole fields. We reduced multipoles to acceptable levels following Halbach's suggestion of "tuning" the field profile by selective motion of the individual magnets based on rotating coil measurements. With the 16 segment construction it is possible to tune out all multipoles between n=3 (sextupole)and n=10; in practice they were reduced to $\leq$ 1 Gauss/multipole at 4 cm or 75% of pole-tip radius compared to the 6000 Gauss quadrupole field.

A crucial point is the stability of the quadrupoles in the magnetic field of the CLEO detector. After installation of the REC quadrupoles we made rotating coil measurements with the solenoid off, and energized to 10 kG. Changes, if any, were at the 1 Gauss level. This tests the mechanical as well as the magnetic rigidity of the quadrupoles since each of the magnet pieces experiences large torques.

The most problematic aspect of the installation of the REC quadrupoles has been the degree to which the machine and the experimental detectors have intertwined with each other; the inner face of the REC quadrupole is 65 cm from the interaction point (Fig. 3).

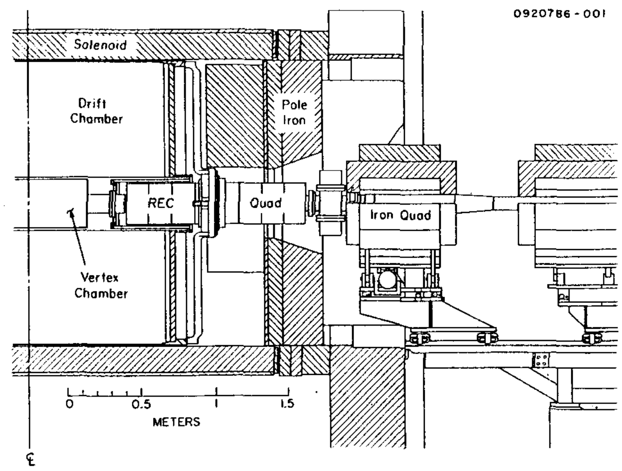

Fig. 3: Schematic view of the South Interaction Region at CESR

We have just begun operation of CESR with the REC quadrupoles, starting conservatively with a lattice giving $\beta_v^* = 3$ cm so as to duplicate previous luminosity conditions, and the luminosity performance indeed appears to be very similar to that of the "old" CESR.

Moving to lattices with lower β_v^* will probably take some time because it is likely that bunch shortening through increased RF voltage will be necessary. CESR now operates with a ratio of $\beta_v^*/\sigma_z \doteq 3$ cm/2 cm = 1.5. As this ratio approaches 1, luminosity is lost due to the hourglass shape of the bunches as they collide and at some point bunch lifetimes will deteriorate due to synchrobetatron coupling of electrons with large energy oscillations. We plan to install a second RF cavity in CESR so that we can maintain β_v^*/σ_z approximately constant as we lower β_v^*; this waits on a successful fix for our RF cavity problem.

The main problem with the RF cavities involves the cylindrical ceramic feed window which separates the cavity vacuum from the waveguide. At high power levels and in the presence of higher mode RF generated by electron bunches passing through the cavity cells, occasional arcs sputter copper from nearby surfaces onto the ceramic window which then heats up and eventually breaks. The problem seems to be greatly aggravated by large currents in the storage ring; obviously this is now a major limitation to improved operation of CESR and we are working on modifications to the window structure.

Beam-Beam Simulations

We have developed an extensive computer simulation of CESR including magnet non-linearities and a 3-dimensional beam-beam interaction with the hope of deriving some understanding of beam-beam limitations to luminosity and of performing tune plane explorations. The simulation became fully practical with the appearance of a supercomputer center near the Cornell campus. Results so far[5] give some evidence for the importance of different mechanisms leading to synchrobetatron resonances

1) The simulations agree well with CESR in the region near our operating point (Q_x = 9.39, Q_y = 9.36), for example the growth of vertical

beam height with current is well modelled.

2) Based on this success a computer scan was made for a better operating point, The region near (Q_x = 9.40, Q_y = 9.15) was found to be promising. The vertical tune is close to the third synchrobetatron resonance since the synchrotron tune is .05.
3) The machine performance did not compare well with the simulation because of the strength of the synchrobetatron resonances.
4) Because the simulation includes beam-beam driven synchrobetatron resonances we concluded that other coupling mechanisms must be important.
5) After including in a preliminary way the coupling due to wakefields[6] we find that wakefields of a reasonable magnitude lead to a reduction in luminosity consistent with the observed performance of CESR.

Low Emittance Operation

Before shutdown for installation of the micro-beta insertions, we made a test in which the emittance of a single 5.2 GeV beam in CESR was lowered by moving the horizontal and vertical tunes from our normal operating point of near 9.4 up to 13.3. Emittances of 5×10^{-8} m-rad in the horizontal (a factor of 4 reduction) and 1×10^{-9} in the vertical were achieved, and reasonable injection rates were obtained with scrapers in the arcs forming a limiting vertical aperture of 1 cm.[7] A problem which was not anticipated was a significant decrease in beam lifetime with increasing bunch current, reaching about 1 hour at 10 ma. This is in fact consistent with Touschek scattering. These measurements demonstrate that we could operate a high brightness undulator in CESR; this would not, however, be compatible with high energy physics operation and a final decision has not yet been made.

Superconducting RF Program

The superconducting RF program at Cornell has included a mix of basic research on materials and problems and of building and testing cavities for storage ring applications. The cavities built for the most recent beam test (1984 in CESR) have 5 cells at 1500 MHz with achieved gradients of 5-15 MV/m, Q's 3×10^9, and waveguides for extracting the higher mode RF from the beam. The technology for these "conventional" cavities is now being transferred to industry[8] in connection with the proposed Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia which is to provide 4 GeV electron beams for nuclear stucture studies. The machine is a recirculating linac with 200 meters of superconducting cavities.[9] Cavity structures meeting the specifications of 5 MV/m and 3×10^9 Q have already been produced by Dornier, Interatom, and Babcock and Wilcox.

The Cornell group will not be directly involved with the construction of CEBAF and is planning to continue its systematic attack on the problems which limit superconducting RF gradients to values far below those corresponding to critical magnetic fields in the surface--50-75 MV/m in Niobium, depending on the structure. A major motivation is the recent proposal that superconducting cavities reliably achieving accelerating gradients of 30-40 MV/m could be a highly competitive technology for construction of a TeV energy linac.[10] The interesting point is that this linac would be in many respects more conventional, i.e. use fewer exotic technologies, than a linac with comparable capabilities and cost using copper cavities.

Using copper cavities it is very difficult to efficiently transfer RF power to the beam because of the high power dissipation in the walls. Achieving reasonable capital and operating costs pushes the design very hard in the directions of:

1) very short RF pulses requiring efficient drivers with high peak power;
2) many closely spaced electron bunches per RF pulse;
3) smaller, higher frequency RF cavities with less stored energy and more severe wakefield problems;
4) transfer of a significant fraction of the cavity power to each bunch;
5) low beam power (a small number of electrons per bunch) and therefore,
6) extremely small emittance to achieve useful luminosities.

Thus, for example, although copper cavities are capable of gradients over 100 MV/m, this becomes economical only at frequencies well above 10 GHz.

For superconducting cavities, transfer of power is efficient and the economic limitations are the higher structure cost and the capital and operating expense for refrigeration to extract from the 2°K Helium bath the power dissipated in the cavity walls. For attainable values of the cavity Q ($\leq 10^{10}$) the refrigeration costs for DC operation of a TeV linac are outrageous but with pulsed RF operating at 1% duty factor they are no longer the principle actors in the cost equations. A relatively low repetition rate, say 30 Hz, limits the power wasted due to dumping of stored RF energy so there is not a strong motivation to move to higher frequency RF or to very low beam powers. In addition the typically 1/2 msec long RF pulses permit electron bunches to be well separated, reducing interactions between bunches via the cavity structure.

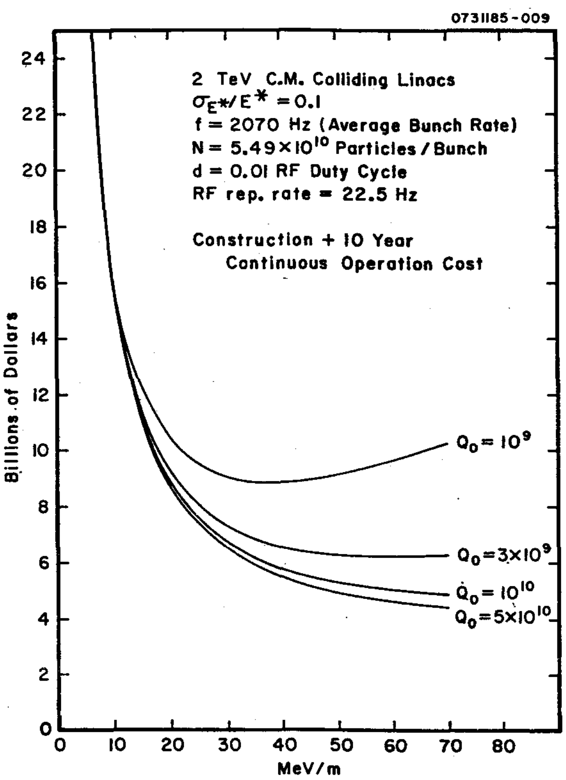

Fig. 4: Cost of a superconducting modulated, 2 TeV CM, 10^{33} $cm^{-2}sec^{-1}$ collider, for a 10% collision point energy spread, vs. gradient, for various values of Q.

Table I[10]

Parameters for a superconducting modulated 2 TeV linear collider. Case I is based in superconducting cavities achieving gradients of 30 MV/m at Q values of 1 x 10^9 and Case II is for a gradient of 65 MV/m at Q of 5 x 10^9.

Parameter	Case I	Case II	Units
Energy (CM)	2	2	TeV
Luminosity	10^{33}	10^{33}	$cm^{-2} sec^{-1}$
σ_{E^*}/E^*	10	10	%
β^*	1	1	cm
D	1.032	1.032	
σ_z	2	2	mm
ϵ_n	$3x10^{-5}$	$3x10^{-5}$	rad-m
g	30	65	MV/m
Q_0	$1x10^9$	$5x10^9$	
Length of RF Structure, 2 Linacs	66.7	30.8	km
RF wavelength	10.5	10.5	cm
AC power consumption	183.9	189.8	MW
Total average RF power	85.3	102.7	MW
Number of 200 kW klystrons	428	514	
Beam power	36.4	36.4	MW
Dumped stored energy	48.9	66.3	MW
RF dissipated at low temperature	17.6	7.6	kW
RF pulse rate	36	22.5	Hz
RF duty cycle	0.01	0.01	
Average beam bunch rate	2070	2070	Hz
Time between beam bunches	4.83	4.83	μs
Particles per bunch	$5.49x10^{10}$	$5.49x10^{10}$	
Number of damping ring pairs	58	93	
Capital cost	5.39	3.22	G$*
10 year (cont.) operating cost	1.29	1.33	G$
Capital + 10 year cost	6.68	4.55	G$

*Modulated RF, superconducting colliders. Capital cost based on estimated structure cost of 60K$/meter. Optimization includes 10 year cont. operating cost.

Figure 4 shows, for a 2 TeV cm collider, the dependence of total cost on both accelerating gradient and cavity Q. For gradients greater than 30 MV/m and Q's greater than 3 x 10^9, the dependence is slow.

Table II lists parameters for colliders optimized for gradients of 65 MV/m. Note that the wavelength and beam emittance are similar to values at the SLC.

The most important barrier to raising superconducting accelerating gradients from the now routine levels of 5-10 MV/m to > 30 MV/m appears to be enhanced field emission of electrons from the cavity surface. The Cornell group and several European groups have been studying the problem and possible cures with some success; recently several single cell cavities built of purified Niobium with high thermal conductivity have been processed to surface gradients above 40 MV/m.[11] So it is quite possible that high field superconducting RF will be an option for future linacs.

Acknowledgements

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Discussion

G.A.Voss. Did you have the 7 bunch performance?

S.W.Herb. We had a several week running period with 7 bunches. There was not an additional luminosity loss per bunch compared to the 3 bunch operation. However, after these two weeks our cavity window broke. And so we have to improve our window design before we can move up there again.

Г.М.Тумайкин. Какова пиковая светимость?

S.W.Herb. With 3 bunch operation we really operated at about $3 \cdot 10^{31}$ $cm^{-2}s^{-1}$. During the short 7 - bunch period we worked at about $4 \cdot 10^{31}$ $cm^{-2}s^{-1}$, but that's not practical for the time being.

G.M.Tumaykin. What is the beam lifetime?

S.W.Herb. The beam lifetime is completely dominated by the beam-beam effect. After two hours we must dump the beam. The beam lifetime is up to perhaps 4 hours.

A.G.Chilingarov. When do you expect to return to 7 bunch operation?

S.W.Herb. I hope that within the next half-year we'll be able to.

Е.А.Кушниренко. Скажите, пожалуйста, какие планы CLEO-2 на ближайшее время? Когда он начнет работать? Что-нибудь о CLEO-2, несколько слов.

S.W.Herb. I have a big graph on that. This is the CLEO-2 detector. The main feature of this is that they have taken a big step of moving a high resolution calorimeter which in this case is something like roughly 10 tons of CsI cristal inside the superconducting solenoid with the drift chambers so that the resolution of the calorimeter will not be degraded by the superconducting coil. Crystals are now arriving. I think the timescale is probably one and a half to two years for having everything in place. I'm not quite up-to-date on that, I'm afraid.

Вопрос из зала. Какова величина поля в детекторе в центре камеры?

S.W.Herb. It is supposed to be 15 kilogauss.

Somebody. When do you know whether you can really get bunch lengthening to make the micro-β?

S.W.Herb. We've already run the machine 7 years ago with two RF cavities at full power and didn't see any problems with bunch lengthening at that time.