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SPEAR — PRESENT STATUS AND IMPROVEMENT PROGRAM*

SPEAR Storage Ring Group**

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ABSTRACT

Initial operating experience with the SLAC electron-positron storage ring SPEAR is described. A single-beam coherent instability, which can be suppressed either by control of the ring chromaticity or by feedback, has been observed. A second single-beam coherent instability has been observed at currents around 50 mA and is not yet understood. Current-dependent bunch lengthening and widening have been observed, and experiments indicate that these phenomena may be associated with an increase in the energy spread of the beam. A luminosity of 2×10^{30} cm^{-2} sec^{-1} has been achieved and two-beam interaction effects are described. Procedures to increase the luminosity to the design value of 10^{32} cm^{-2} sec^{-1} at 2 GeV are discussed. Plans to increase the maximum beam energy of SPEAR to 4.5 GeV are described.

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1. INTRODUCTION

The SLAC Electron-Positron Colliding Beam Project SPEAR was completed in April, 1972, after a construction period of approximately 20 months. Since the completion of the project we have had 12 weeks of testing time and during that period we have attained a luminosity (yield per unit cross section per unit time) of $\mathscr{L} = 2 \times 10^{30}$ cm^{-2} sec^{-1} which makes SPEAR the highest luminosity storage ring now operating. SPEAR has achieved sufficient luminosity to make feasible an exciting experimental program, and this program is scheduled to begin in December of this year. This paper discusses our experience with SPEAR during the brief 12 weeks of operating since its completion, as well as our plans to increase the maximum operating energy of the ring.

Our understanding of colliding beam devices has an impact beyond those of us who are interested in electron-positron collisions, for in the past few years — especially since the turn-on of the ISR — more attention has been given to the possibility of achieving enormous center-of-mass energies through the use of colliding beam techniques. To make the colliding beam technique useful to study elementary particle physics, high luminosities must be achieved and this in turn requires that we understand the limitations on the performance of colliding beam devices. SPEAR may be considered in a sense as a test vehicle for the colliding beam devices of the future for we have incorporated in its design those structural features, devices and procedures which experience with Soviet, Italian, French, and American colliding beam projects has indicated could contribute to the achievement of high luminosity. In brief, some of our observations agree quantitatively with predictions (effect of low-beta on the two-beam incoherent instability and the effect of sextupoles on single-beam coherent instabilities, for example); some of our observations agree qualitatively with predictions (the dependence of bunch lengthening on current, for example); and some of our observations are not now understood (a fast-growing single-beam coherent instability at currents of about 50 mA, for example).

2. GENERAL DESCRIPTION

In this section we summarize the salient features of the SPEAR project. More details are available elsewhere.[1]

SPEAR is a single ring composed of n=0 bending magnets and quadrupoles to provide focusing — it is shown schematically in Fig. 1. Two arcs composed of standard modules connect two variable-dispersion, low-beta insertions. The rf system runs on the 40th harmonic of the orbit frequency. In operation only one out of the forty possible bunches of electrons and positrons is filled so that the electron and positron beam, which circulate in a common aluminum vacuum chamber, collide only at the center of the two low-beta insertions. These low-beta insertions are designed to achieve high luminosity in the face of the incoherent two-beam instability which has been the limit on the beam-beam interaction rate in all electron colliding beam devices built to date. The tune of the ring is variable from 5 to 5.5; the vertical beta function and horizontal beta function at the interaction points are variable from 5 cm to 50 cm and 1 m to 8 m, respectively; and the dispersion at the interaction point can be varied from 0 to 5 cm per percent of momentum spread.

The maximum operating energy of the ring is 2.8 GeV (limited by the available rf voltage) and the maximum luminosity is 10^{32} cm^{-2} sec^{-1} at an energy of 2.3 GeV and 250 milliamperes circulating beam current. The luminosity drops to 10^{31} at an energy of about 2.8 GeV and also at an energy of about 1 GeV. These luminosities assume that the luminosity is limited by the incoherent two-beam instability and that the corresponding tune shift is about 0.025. To reach design luminosity requires that the beam area be greatly increased over that which obtains in the configuration into which we inject (corresponding to zero dispersion at the interaction region). We can control the effective beam height either by introduction of external horizontal-vertical betatron coupling or by introducing a small crossing angle of up to 3 mrad. The width of the beam can be controlled by varying the dispersion of the lattice or by artificially exciting incoherent betatron oscillations. In practice, we must inject with the two beams separated at the interaction point; build up to currents far above the incoherent two-beam limit which would apply if the beams were colliding in the injection configuration; change the coupling, beta functions and dispersion with the beam stored; change the energy to the design operating energy and only then bring the beams into interaction.

These lattice manipulations involve complex interrelations among the currents of eleven separate magnet systems and are much too difficult to be accomplished manually in any reasonable time. The control of the magnets, as well as most of the other control and monitoring functions in SPEAR, is accomplished by an XDS Sigma-5 computer (48K of core, 32-bit words, 1 μsec cycle time) which will also handle data logging and on-line analysis for the elementary-particle physics experimental program. This computer system allows the storage ring operator to choose any values of tunes, betas and dispersions and to vary any subset of these parameters while holding the others constant.

SPEAR is equipped with a variety of devices to control beam instabilities. These include sextupole magnets to control the variation of tune with energy, electric quadrupoles to separate the betatron frequencies of the electron-positron beams, octupole magnets to provide variable Landau damping and a fast servo-system which works independently on the electron and positron beams to control coherent betatron instabilities.

3. OPERATING EXPERIENCE

3.1 Single Beam

Most of the studies of beam behavior have been carried out at a beam energy of 1.5 GeV, although beam energies up to 2.7 GeV have been attained. Injection rates of up to 50 milliamperes per minute (average circulating current) have been obtained into a single electron bunch with positron filling rates being somewhat lower. Injection energy is fixed at 1.5 GeV; the injection pulse rate is 20 pps dictated by radiation damping time; and a typical injection pulse is one to two milliamperes in height and 10 nsec long.

Uncorrected distortions of the equilibrium orbit caused by imperfections in the magnet fields and misalignment were measured to be as large as 1.4 cm in the radial coordinate and 0.7 cm in the vertical coordinate. Each of the bending magnets is provided with a small correcting winding. Three of these were chosen by analysis of the distortion data and powered to reduce the largest radial distortion to a few millimeters. The vertical distortions were also reduced to a few millimeters by means of correcting windings in the interaction-region quadrupoles.

A beam instability is observed which is entirely consistent with the expected behavior of the head-tail effect.[2] The chromaticity of the beam is controlled by a system of sextupoles distributed around the ring, three to a cell. Also provided is a wide-band transverse feedback system for damping coherent bunch center-of-charge motion. This system acts independently on electrons and positrons and on radial and vertical motion. It has a risetime of 12 nsec and can produce decay times (e^{-1}) as short as 3 msec for 1 mA average beam. A series of experiments carried out to study the chromaticity-dependent instability is summarized in Table 1. The momentum-compaction coefficient during these experiments was 0.042. We may interpret these results with reference to the head-tail effect by assuming that the driving forces in both radial and vertical coordinates have signs such that the barycentric mode (in which all particles in the bunch move together) is unstable when the chromaticity is negative and that all the other modes are therefore stable. The feedback system is capable of stabilizing the barycentric mode.

The column of Table 1 labeled "Threshold Current" shows evidence of another kind of single-bunch instability in the SPEAR storage ring. With both chromaticities negative, as in the third line of the table, and the feedback on to stabilize the barycentric mode, we might expect to have defeated the head-tail instability, and yet there exists a limiting current beyond which the storage ring cannot be filled. We observe a similar limiting current with both chromaticities positive and it is independent of the use of the feedback system. This limit varies somewhat from day to day and with adjustments of the ring, and it usually lies in the range between 35 mA and 60 mA. The phenomenon is characterized by an abrupt loss of a fraction of the stored current when the threshold current is reached. We normally operate with both chromaticities positive to achieve the highest possible threshold current and, under these circumstances, the threshold is substantially uninfluenced by either the feedback systems or the octupole system. This instability is as yet not understood and is under study.

Figure 2 shows the measured dependence of the rms length in time of a single bunch as a function of circulating current at constant rf accelerating voltage. The measurements were made with a photodiode which is expected to introduce only negligible instrumental broadening of the signal. For comparison, a curve is plotted having the current dependence expected if the bunch lengthening is due to electromagnetic fields induced in the chamber by the bunch.[3] The curve is not a fit to the data, but is shown only for comparison. The measurements of Fig. 2 were taken when only one rf cavity had been installed in the storage ring. Subsequently, a second identical cavity has been installed, and new measurements show that the addition of the second cavity made no substantial difference in the bunch length under given conditions of the lattice and total rf voltage. At the same time that the bunch lengthens, it also widens as seen by synchrotron light which could indicate an increase in the energy spread.

To further investigate these phenomena we have done two experiments using more than one bunch in the ring. In the first of these experiments the length of one bunch was measured as a function of current in a bunch ahead of the one being measured (20-nsec time separation). No change in length of the constant current bunch was observed indicating that the fields responsible for the lengthening are local fields. We also simultaneously measured at low rf voltage the quantum lifetime of a low current (short, narrow) bunch and of a high current (long, wide) bunch. The high current bunch has a shorter quantum lifetime strengthening the hypothesis of an increased energy spread associated with the lengthening and widening.

As explained previously, the SPEAR beams need a larger effective interaction area to obtain design luminosity than the area which results from natural beam size with zero dispersion at the interaction region; and one method of obtaining a greater width is to adjust the lattice to produce a large dispersion at the interaction region (high-η^*). The injection rate into the high-η^* configuration is much lower than that into the zero-η^* configuration, so one intended mode of operation of the storage ring is to fill in the zero-η^* configuration and then, under computer control, to vary parameters to carry it to the high-η^* configuration. The computer program to guide this parameter variation allows the operator to choose set points for the five optical parameters ν_x, ν_y, β_x^*, β_y^*, η^*, and then carry the ring lattice to that condition from wherever it happens to be. The computation involves solving simultaneous nonlinear equations relating the optical parameters to the magnet strengths, and some combinations of the five selectable parameters are, in practice, unobtainable by the program. Figure 3 shows the $\beta_x^* - \eta^*$ plane upon which ν_x, ν_y and β_y^* are constant. The hatched areas A, B and C are the unreachable ones, and the line consisting of three straight segments and extending from the injection configuration to the operating configuration shows a typical path along which the beam is carried after storage. Problems encountered along this journey have been mainly due to programming difficulties and power-supply problems. Along the path eight power supplies are varied simultaneously and one is reversed.

3.2 Double Beam

The colliding beam performance of SPEAR with natural beam size and zero dispersion at the interaction region has been about as expected with a noteworthy exception, which is discussed later. Luminosity is measured by means of Møller scattering at small angles. In Fig. 4, measured values of normalized luminosity are plotted versus the vertical beta function at the interaction point. By normalized luminosity we mean the luminosity divided by the product of the circulating currents ($\mathscr{L}/i_+i_-$). The currents used in these experiments were chosen to be sufficiently below the incoherent limit so that the beam cross section was determined only by the tuning of the ring lattice. Theoretical curve is obtained by assuming that the coupling parameter

$$A = \frac{\sigma_y}{\sigma_x}\left(\frac{\beta_x}{\beta_y}\right)^{1/2}$$

is independent on the value of β_y^*. This is probably not a valid assumption, especially for coupling fields introduced by the quadrupoles adjacent to the interaction regions and, in fact, the experimental points can be matched exactly by varying A appropriately.

In general it appears that the vertical tune-shift per interaction region obtainable with a flat beam is about $\Delta\nu_y = 0.025$ as inferred from the luminosity, the current and the value of β_y^*. If currents much larger than those which would give this tune-shift are stored, one beam is seen to become diffuse vertically and very little increase in luminosity is obtained.

The best luminosity to date has been obtained by operating just below the coupling resonance $\nu_x = \nu_y$. In this "autocoupling" regime, newly injected particles do not feel the coupling effects of the stored counter-rotating beam until they damp down and are tune-shifted up to the resonance line by interaction with the other beam. The damped beams are nearly round, and their diameter seems to continue to increase as current is added, up to about 18 mA, at which point a luminosity of 1.8×10^{30} cm^{-2} sec^{-1} has been obtained with $\beta_y^* = 37$ cm. Figure 5 shows how the luminosity increases with stored current in this mode of operation. It does not show the saturation effect common under uncoupled conditions. With slightly different currents in the two beams we have succeeded in reaching a luminosity of 2×10^{30} cm^{-2} sec^{-1} in this mode.

4. SPEAR IMPROVEMENT PROGRAM

The initial design of SPEAR incorporated the possibility of an eventual increase in both the maximum operating energy of the ring and the rf power available. We expect to begin both these projects in the next few months. The goals of the improvement program are to increase the maximum operating energy from the present to 2.8 GeV to 4.5 GeV each beam, and to increase the rf power from 160 kW to 500 kW. The results of these two improvements are a luminosity versus energy curve, which is illustrated in Fig. 6. We have again assumed the luminosity to be limited by the incoherent two-beam instability with tune-shift $\Delta\nu = 0.025$ and an aperture limit given by the present size of the vacuum chamber. At energies above about 3 GeV the luminosity is limited by the available rf power.

The maximum operating energy of 4.5 GeV is determined by saturation in the magnets. The increase in the peak magnetic field is a relatively simple project which requires the addition of about 2.5 MW of dc power to the existing complement of power supplies. This is straightforward and we will not discuss this part of the project further.

The rf problems associated with the energy increase are much more formidable. The rf voltage required to make up for synchrotron losses goes from approximately 420 kV per turn at the present maximum energy of 2.8 GeV to about 2.8 MeV per turn at 4.5 GeV. Still higher voltages are required to achieve a reasonable quantum lifetime. Both the shunt impedance per unit length of our present rf cavity system and the available straight-section length make it entirely impractical to achieve these voltages at the present frequency of 50 Mc.

We have conducted a study of cost versus frequency for a new rf system constrained by the available straight-section length, and find a broad cost minimum at about a frequency of 300 MHz. We have selected a frequency of 358 Mc (280th harmonic) and plan to use a set of rf cavities patterned on those used in the Los Alamos proton linac. Our cavity design is illustrated in Fig. 7. We are continuing the cavity design study to see if we can dispense with the side-couple feature and use slot coupling, since that simplifies the cavity fabrication.

In our optimization study we have reviewed the available rf power sources (tubes and klystrons) and conclude that there are none now available which meet our needs. We are therefore planning to develop a klystron in the SLAC laboratory. The tentative parameters of this tube are shown in Table 2. Four of these klystrons are required, each feeding a straight section containing a module consisting of 5 Los Alamos type cavities.

The improvement program is scheduled to begin soon (subject to the availability of funds) and to be completed by July 1974.

5. REFERENCES

1. SLAC Storage Ring Group, Proceedings of 8th International Conference on High-Energy Accelerators, CERN, 1971 (European Organization for Nuclear Research, Geneva, 1971); p. 145.
2. C. Pellegrini, Nuovo Cimento, Series 10, 64A, 447 (1969).
3. K. Robinson, "Bunch Lengthening in Storage Rings," Cambridge Electron Accelerator Internal Report CEAL-TM-183 (July 1969); C. Pellegrini and A. Sessler, Nuovo Cimento, Series 11, 3A, 116 (1971).

TABLE 1

Chromaticity-Dependent Instability Thresholds

$p \frac{\partial \nu_x}{\partial p}$	$p \frac{\partial \nu_y}{\partial p}$	Threshold Current (mA)	Feedback Condition	Loss
-1.05	-1.05	1.4	off	Vertical
-1.05	-1.05	1.5	only vertical	Radial
-1.05	-1.05	28.0	on	Vertical
1.05	-1.05	1.6	off	Vertical
1.05	-1.05	15.4	on	Vertical
-1.05	1.05	1.5	off	Radial
-1.05	1.05	35.8	on	Vertical
1.05	1.05	35.8	off	Radial
1.05	1.05	35.8	on	Radial

TABLE 2

Tentative Klystron Parameter for 4.5-GeV Operation

Power	150 kW
Voltage	45 kV
Gain	40 dB
Efficiency	50%
Frequency	358 ± 0.5 Mc
Length	2.9 m

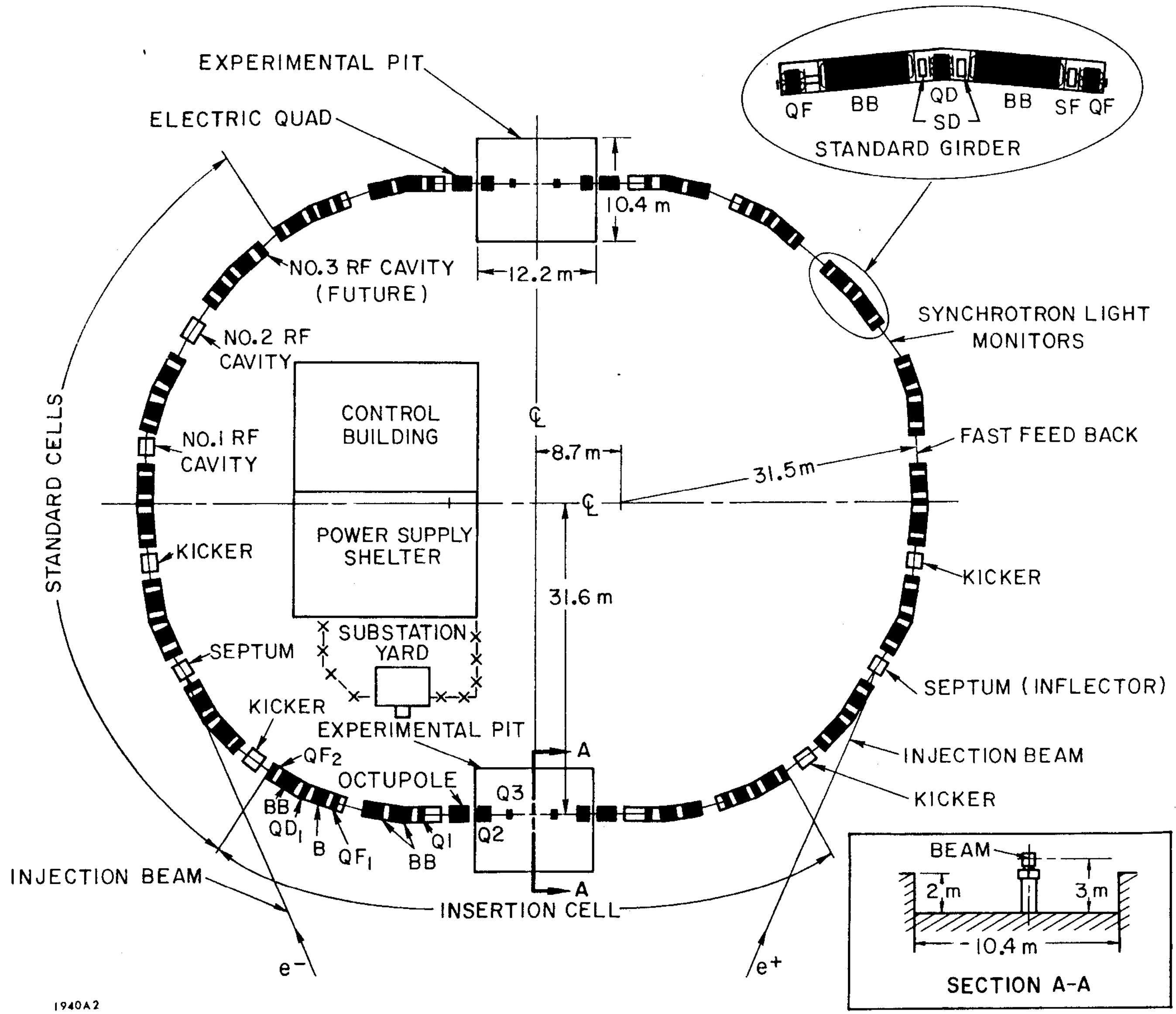

FIG. 1--Layout of SPEAR.

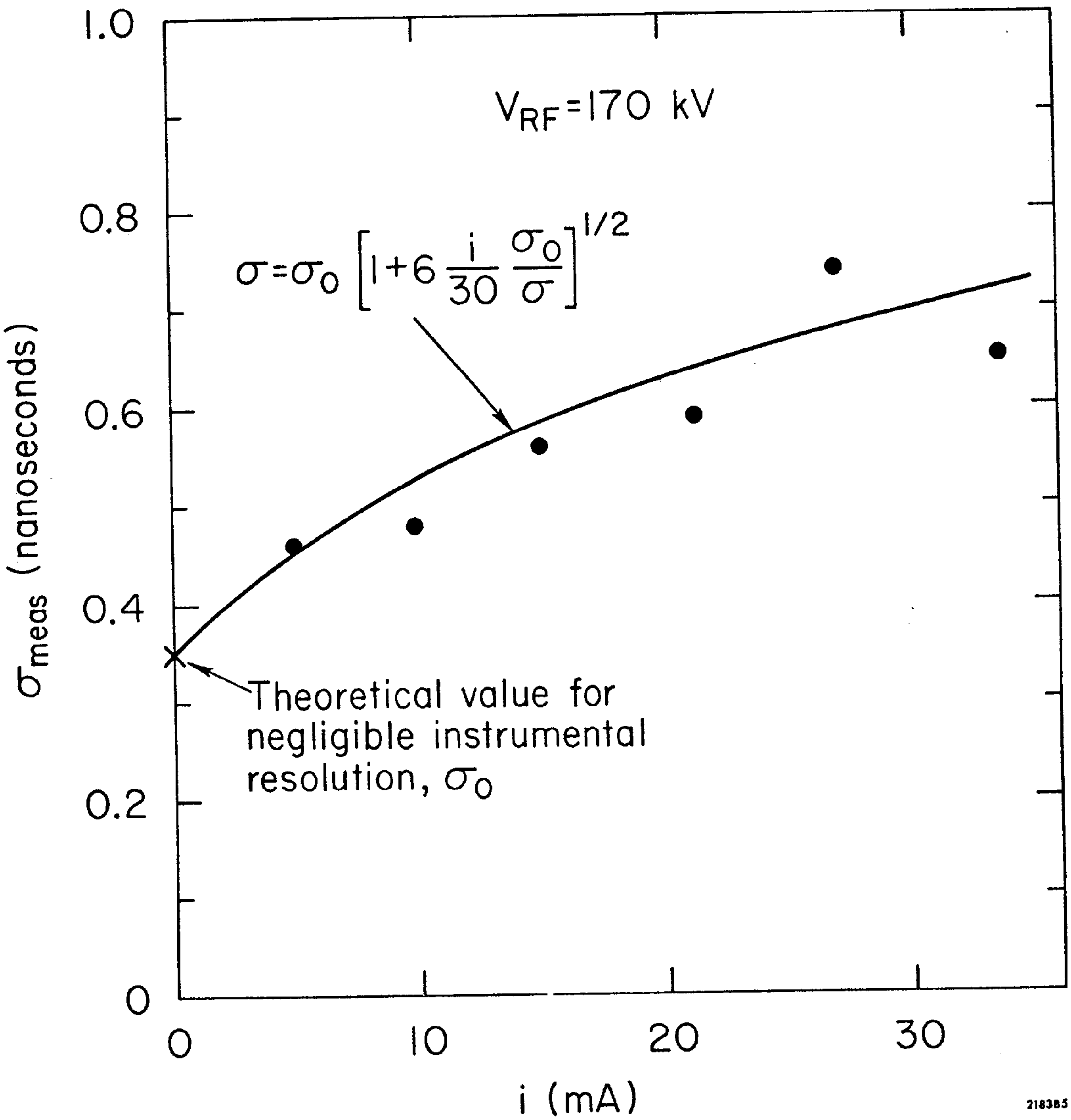

FIG. 2--Length of bunch vs average bunch current.

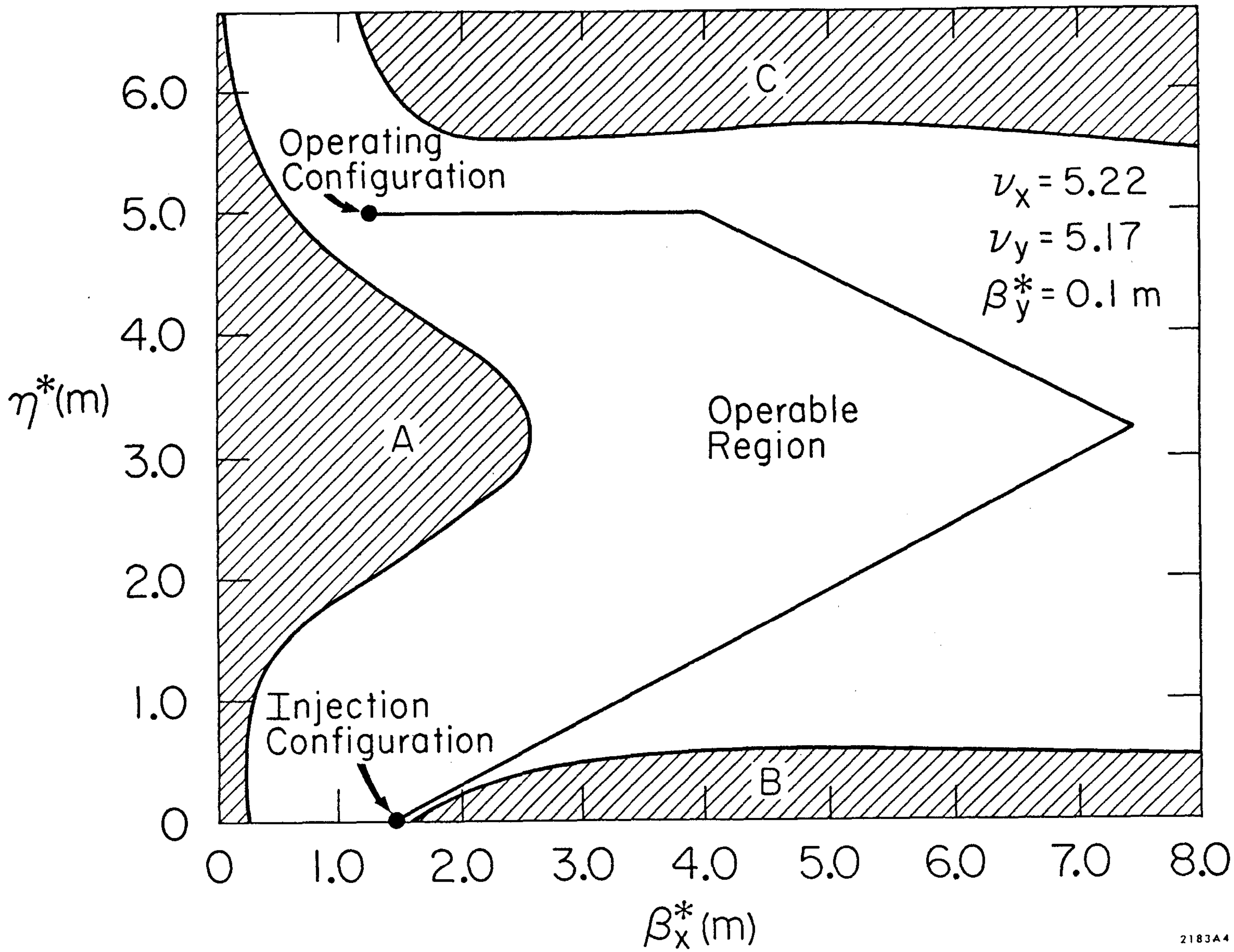

FIG. 3--Path from zero-dispersion to high-dispersion operating point. (The regions labeled A, B, and C are those for which the computer can find no solution consistent with the tunes and β_y^* required.)

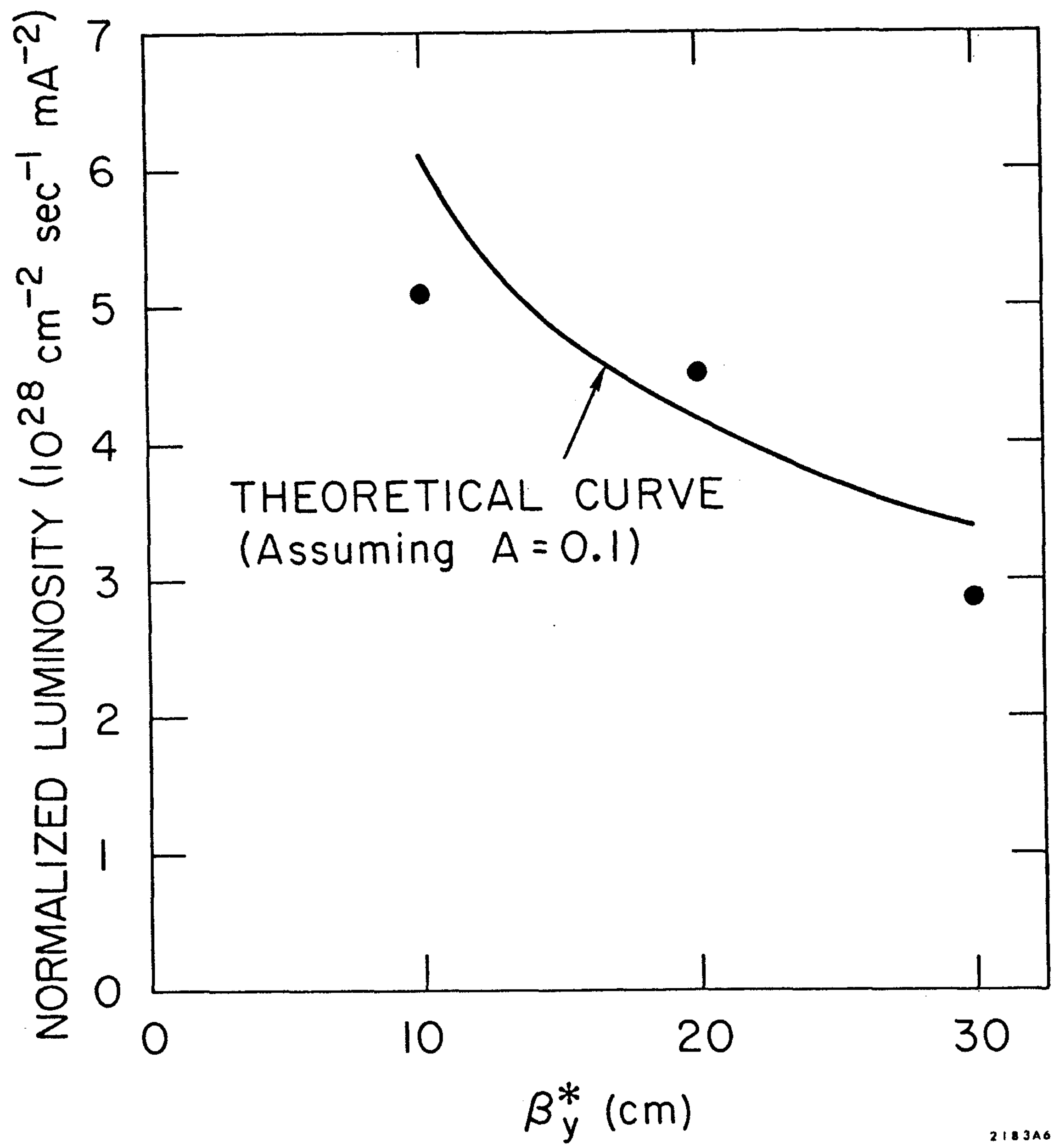

FIG. 4--Normalized luminosity ($\mathscr{L}/i_+i_-$) vs β_y^* at the collision point. (Beam currents are below those which give rise to the incoherent two-beam instability.)

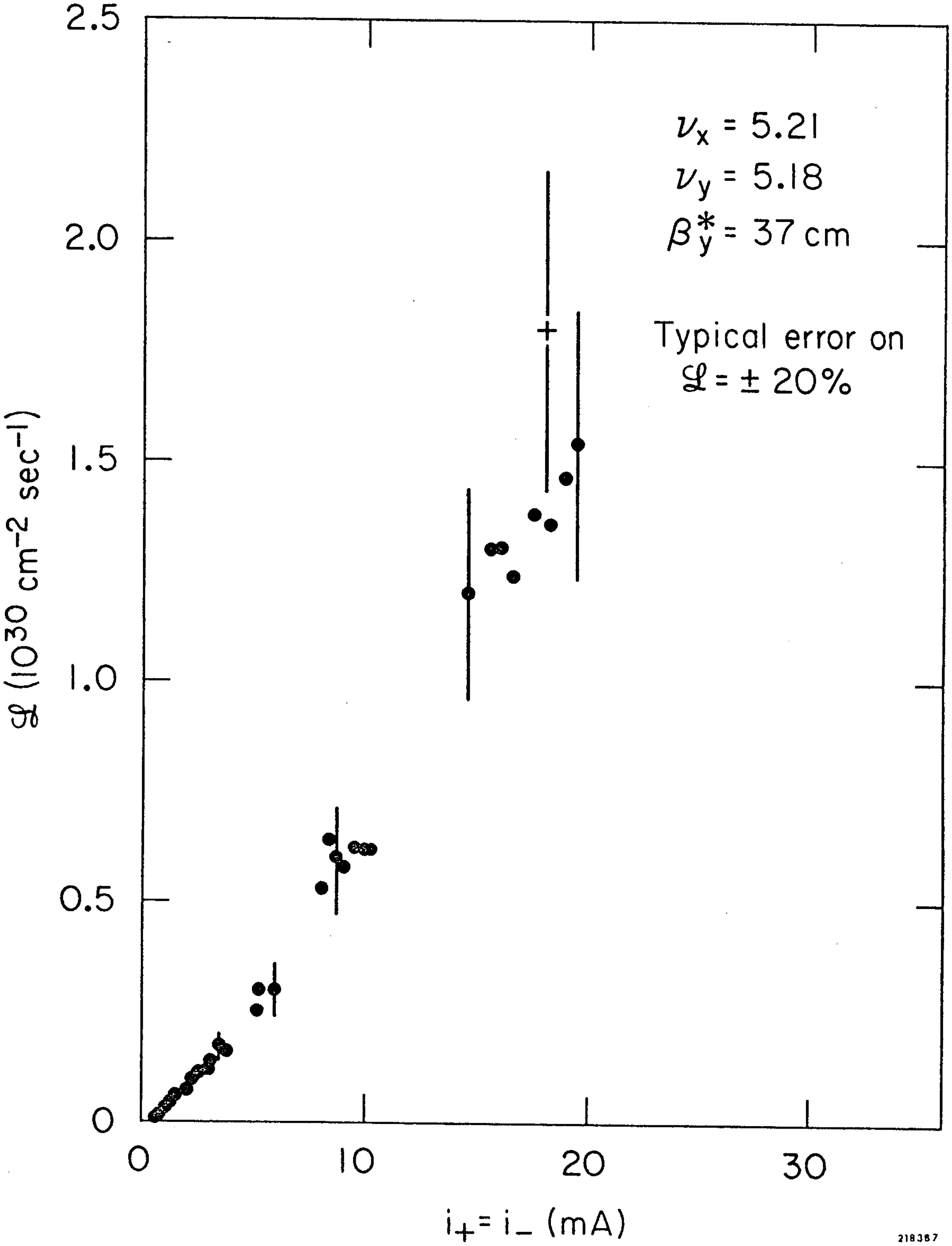

FIG. 5--Luminosity vs beam current in the autocoupling regime. (Electron and positron beam currents are equal.)

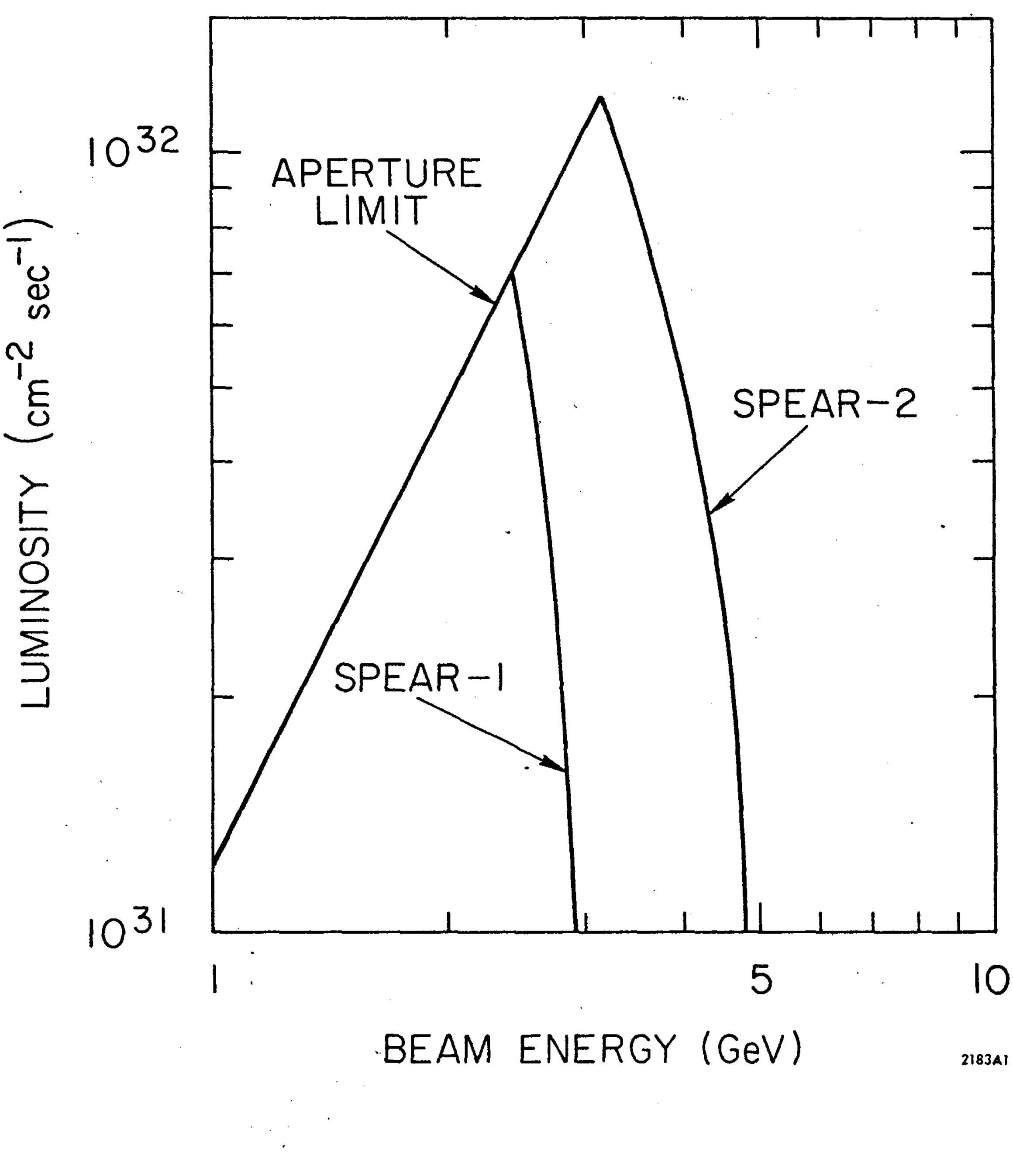

FIG. 6--Design luminosity vs energy for the improved SPEAR.

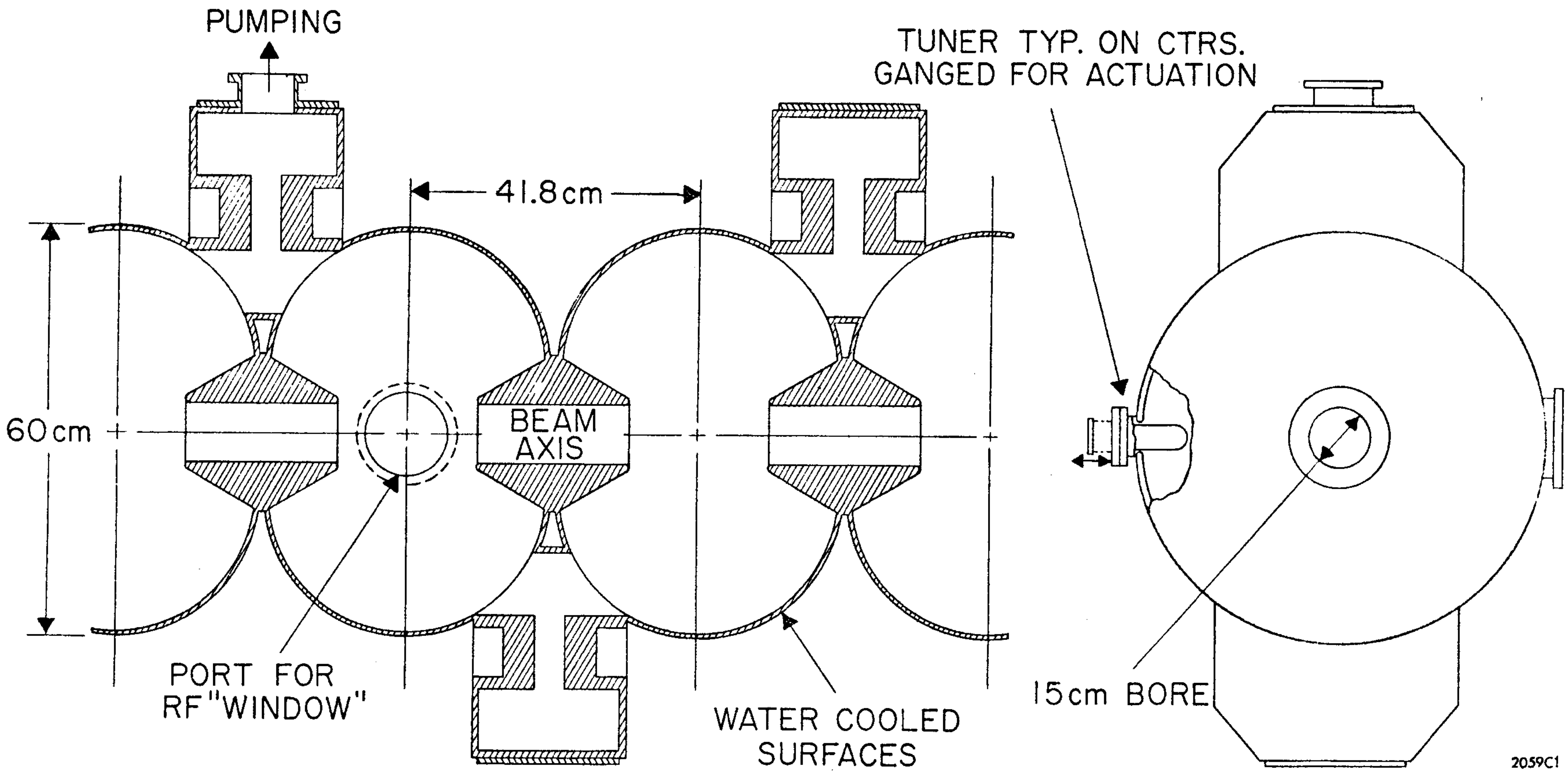

FIG. 7--Preliminary cavity design for high-frequency rf system.