SLAC-PUB-240
November 1966

DESIGN CONSIDERATIONS FOR HIGH ENERGY ELECTRON-POSITRON STORAGE RINGS*

B. Richter
Stanford Linear Accelerator Center, Stanford, California

Talk presented at International Storage Ring Conference at Saclay, France, (September 1966).

*Work supported by U. S. Atomic Energy Commission.

I. INTRODUCTION

High energy electron-positron storage rings give a way of making a new attack on the most important problems of elementary particle physics. All of us who have worked in the storage ring field designing, building, or using storage rings know this. The importance of that part of storage ring work concerning tests of quantum electrodynamics and mu meson physics is also generally appreciated by the larger physics community. However, I do not think that most of the physicists working in the elementary particle physics field realize the importance of the contribution that storage ring experiments can make to our understanding of the strongly interacting particles. I would therefore like to spend the next few minutes discussing the sort of things that one can do with storage rings in the strongly interacting particle field. While most of you, I am sure, are familiar with what I will say, there are probably some skeptics in the audience.

The production of strongly interacting particle pairs proceeds through the annihilation diagram shown in Fig. 1, wherein the electron and positron annihilate to form a single photon, and this photon then materializes as a pair of particles. The simplicity of the one photon intermediate state makes the interpretation of these experiments particularly simple. The angular distributions contain only low powers of cos θ, and the reaction products come out broadly distributed in angle rather than very sharply peaked in the forward direction as in the case where particles are produced in reactions initiated by strongly interacting particles.

The simplest experiment for a high energy electron-positron storage ring is a direct test of symmetry schemes. This experiment requires only that the relative yields of various strongly interacting particle pairs be measured at a given storage ring energy. Table I shows some of the predictions of SU(3). SU(3) predicts only the relations within a given column of Table I. Relations between columns are given by higher symmetry schemes. For example, U(12) predicts that the relative yield of proton, anti-proton pairs and N^*_{33} pairs are in the ratio of one to four. While I realize that U(12) is unfashionable at the moment,I have used it because I know the answer it gives and to illustrate the point that the measurement of relative cross sections provides a direct test of higher symmetry schemes. All symmetry schemes predict the relative electromagnetic form factors of members of a given multiplet.

Another interesting experimental possibility is to test the principle of charge conjugation invariance for strongly interacting particles, by a search for such final states as $\rho^o\rho^o, \phi\phi, \rho^o\phi, \pi^o\eta^o$, etc... All of these states have $C = +1$ while the one photon intermediate state has $C = -1$. Detection of the production of such states via the one photon reaction is a direct indication of the violation of charge conjugation invariance. However, such states can be produced with no violation of C by means of two photon reactions. Calculations made at Stanford this summer by Chen on the production of $\rho^o\rho^o$ indicate that using the large C violating coupling proposed by Lee, the production of $\rho^o\rho^o$ through one photon exchange is very much larger than two photon exchange. This type of experiment is a much more sensitive test of C violation than is the charge asymmetry in η decay.

Another interesting class of experiment is the search for new resonances. This can be done in a storage ring by studying the yield of particles as a function of the storage ring energy and looking for an enhancement in the yield at a particular energy.

TABLE 1

SU(3) Predictions for $e^- e^+$ Annihilation

$$\left[\sigma^o = \sigma_M(1+\cos^2\theta) + \sigma_E \sin^2\theta\right]$$

Only the relationships between cross sections in a given column are given by SU_3; relations between different columns, e.g., $\sigma_E(\bar{p}p)/\sigma_M(\bar{p}p)/\sigma_E(\bar{p}N^*)/\sigma_E(\bar{N}^* N^*)$, etc., are not predicted.

	σ_E	σ_M		σ_E	σ_M		σ_E	σ_M		σ_E	σ_M		σ_E	σ_M
$\bar{p}\,p$	1	1	$\bar{N}^{*++} N^{*++}$	4	4	$\bar{N}^{*+}\,p$	1	1	$\pi^+\pi^-$	1	0	$\rho^+\rho^-$	1	1
$\bar{n}\,n$	0	4/9	$\bar{N}^{*-} N^{*-}$	1	1	$\bar{N}^{*o}\,n$	1	1	K^+K^-	1	0	$K^{*+}K^{*-}$	1	1
$\bar{\Sigma}^+\Sigma^+$	1	1	$\bar{N}^{*-} N^{*-}$	1	1	$\bar{Y}^{*+}\Sigma^+$	1	1						
$\Sigma^o\Sigma^o$	0	4/9	$\bar{Y}^{*+} Y^{*+}$	1	1	$\bar{Y}^{*o}\Sigma^o$	1/4	1/4						
$\bar{\Lambda}^o\Lambda^o$	0	1/9	$\bar{Y}^{*-} Y^{*-}$	1	1	$\bar{Y}^{*o}\Lambda^o$	3/4	3/4						
$\bar{\Sigma}^-\Sigma^-$	1	1/9	$\bar{\Xi}^{*-}\Xi^{*-}$	1	1	$\bar{\Xi}^{*o}\Xi^o$	1	1						
$\bar{\Xi}^o\Xi^o$	0	4/9	$\bar{\Omega}^-\Omega^-$	1	1									
$\bar{\Xi}^-\Xi^-$	1	1/9												
$\bar{\Sigma}^o\Lambda^o$	0	1/3												

I picked these three types of experiments to discuss because most of the XIII th International Conference on Elementary Particle Physics at Berkeley, last month, was devoted to a discussion of these three subjects. Very little that was new was said – and the situation is not very much clearer than it was at the preceding conference in 1964. I believe that an attack on these problems in a new direction is required for understanding of elementary particle physics and I believe that experiments which can be done with a high energy electron-positron storage ring provides this new direction. It is unfortunate that storage ring technology has advanced slowly in the past, for it would be nice to have the answers to these questions now. However, progress in hadron physics has been if anything even slower than progress in storage rings, and I think these problems will still be waiting for us when high energy electron-positron storage rings, which will soon be under construction, are ready.

II. LUMINOSITY REQUIREMENTS

Having discussed why I believe a high energy electron-positron storage ring to be very important to progress in elementary particle physics, I would now like to turn to the two most basic questions relating to the design of a ring – what luminosity (reaction rate per unit cross section) is required, and what should be the maximum energy of the ring. The answer to the first of these questions requires that we estimate the expected cross section for the processes we wish to study. The answer to the second question requires consideration not only of the physics, but of the cost of the facility.

Because of form factor effects, the cross sections for production of strongly interacting final states are expected to be much smaller than the cross sections for those processes which involve studies of quantum electrodynamics, μ meson physics, new lepton searches, etc... If the luminosity of the storage ring is sufficiently high to allow the study of reactions leading to strongly interacting final states, other reactions can be studied with great ease. We therefore try to estimate, below, what these form factors can be expected to be, based on our present tenuous knowledge.

Two major experiments, one at Brookhaven National Laboratory[1] and one at CERN[2] have recently attempted to measure the form factors of the proton for time-like momentum transfers by studying the inverse of a process which would occur in the storage ring. They studied the process where anti-protons annihilate with protons to form an electron-positron pair. These experiments failed to measure the cross section for the process because of its small value and the low intensity of the available anti-proton beam. However, these experiments together with an extrapolation of elastic electron-proton scattering data (space-like momentum transfer) can be used to give a rough guide for what one might expect for the cross section for the process

$$e^+ + e^- \longrightarrow p + \bar{p}$$

This estimate will also serve as a guide for an estimate of the cross sections of all reactions leading to baryons in the final state. Present theoretical ideas indicate that all these cross sections are comparable.

It requires more of a guess to estimate the cross sections for those reactions leading to mesons in the final state. It seems reasonable to assume that, outside regions where meson resonances occur, the meson form factors should not be too different from the nucleon form factors. There is some recent experimental evidence[3, 4] which tends to support this hypothesis and shows that at low momentum transfer the mean square radius of the π meson is about the same as that of the nucleon.

Figure 2 shows the expected cross section for various assumptions about the nucleon form factor. The figure shows a few of the extrapolations into the time-like momentum transfer region of fits to the elastic electron-proton scattering data made by the Harvard Group.[5] The numbers on the curves refer to the numbers of the fit in Ref. 5. The results of the Brookhaven and CERN experiments on anti-proton annihilation to form electron-positron pairs can be used to predict the cross section for anti-proton pair production in the storage rings. At a four-momentum transfer of 6.8 $(\mathrm{GeV}/c)^2$ (corresponding to an electron energy of 1.3 GeV in the storage rings), both the CERN and Brookhaven experiments observed no events. Combining the results implies that:

$$\sigma(e^+ e^- \longrightarrow p\,\bar{p}) \leq 0.14 \times 10^{-33}\ \mathrm{cm}^2$$

with 90% confidence. The Brookhaven Group observed two possible examples of the reaction at a lower energy, but they have not completed the evaluation of a relatively large background. The cross section implied by one event at this lower energy is also shown on Fig. 2.

Curves number 3 and 6 of Fig. 2 are inconsistent with the results of the CERN and Brookhaven anti-proton annihilation experiments. Curve number 2 of Fig. 2 is consistent with the annihilation experiments, but gives very bad agreement with the electron scattering data. The Harvard Group regards curve number 4 as the best fit to the electron scattering data in the space-like momentum transfer region, and we will therefore adopt it as a rough guide for estimating the expected yield of any strongly interacting final state.

Subsequent to my preparation of one of the next few figures, groups at DESY have presented some new electron scattering data which indicate that curve 1 of Fig. 2 is a better fit to the elastic scattering data for space-like momentum transfer. Since this form factor estimate should only serve as a rough guide to what to expect in the region of time-like momentum transfer, I think I do no violence to any one prejudice about physics by continuing to use fit number 4.

In order to do what we set out to do — define a minimum luminosity for a high energy storage ring — we must now define a minimum yield for a reaction. I would estimate this minimum around 0.01 counts per hour. While this number looks very low at first glance, it is not impossible to do experiments at this level, since there are 30 - 50 interesting channels open simultaneously. The physics is important enough to warrant long runs and a 4-month run gives about 25 counts per channel.

However, if the counting rate was significantly below this level, we would probably be unable to do strong interaction physics with the storage ring.

Considering the uncertainty in the cross section estimate, this seems to be a reasonable design figure. If the actual cross section is larger than we have assumed, we will be able to make accurate measurements at the highest energy which the ring can reach. If the actual cross section is smaller than we have assumed, we will, because of the rapid increase with decreasing energy in the cross section, and in the instability limited luminosity if a ring can be filled to the limit of rf power at energies lower than the maximum energy of the ring, reach the limit of detectability at an energy somewhat lower than the maximum the storage ring can reach.

To give some feeling for what these words mean in practice, I will use the proposed Stanford 3-GeV ring as a model. Figure 3 shows the luminosity which goes slightly faster than $1/E^3$ with beam energy. The luminosity at 3 GeV is $1.4 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$. Figure 4 shows the expected counting rate in a typical channel using the estimate of the proton-antiproton cross section as the typical cross section.

With a storage ring designed to give sufficient luminosity to study the strongly interacting final states, the reaction rates for the processes which involve only quantum electrodynamics or μ mesons are expected to be very large. Table II gives the rates in events per second of some of those processes based on the design luminosity of the Stanford ring. These rates are very large in comparison to those expected for strongly interacting final states. One will have to make the trigger system of a general purpose detector for strongly interacting particles insensitive to these types of events in order to study the strongly interacting states. Rejection ratios of 10^5 to 10^6 are required, but those should not be too difficult to achieve.

TABLE II

Counting rates (events per second) for various processes in the angular range $25^\circ < \theta < 155^\circ$

Reaction	Energy (GeV)		
	1	2	3
$e^+ + e^- \rightarrow e^+ + e^-$	4300	135.0	17.0
$e^+ + e^- \rightarrow e^+ + e^-$ ($\theta > 90^\circ$)	160	5.1	0.66
$e^+ + e^- \rightarrow \mu^+ + \mu^-$	76	2.4	0.32
$e^+ + e^- \rightarrow \gamma + \gamma$	220	17.0	2.2

III. CHOICE OF ENERGY

The lower limit for the energy of a new storage ring project has been generally agreed to be about 3 GeV. The designs of the Stanford, C.E.A., DESY and Novosibirsk groups are all based on this energy. The justification for this choice is in the fact that about this energy is required for a meaningfull test of higher symmetries and for a significant extension of tests of quantum electrodynamics and μ meson physics beyond what can be done with the 1.5 GeV Adone storage ring. The real question is what should be the maximum energy of a new storage ring project.

If one uses the cross section extrapolation of the previous section to predict the beam current requirement for a 4.5 GeV storage ring for example, capable of studying strong interactions physics, one finds that currents of 5 to 10 amperes are needed. The cost of such a facility would be very large, and since the extrapolation of the expected cross sections for hadron final states are so uncertain, I think that these very large expenditures are not warranted at this time. The best choice would seem to be to optimize the storage ring design at the energy of 3 GeV with a current sufficient to study the strongly interacting final states.

However, there is a relatively inexpensive way of achieving higher energies for the study of processes which do not involve strongly interacting particles. One can add more power supply to the magnet system and increase the magnetic field without increasing the rf power beyond what is required for strong interaction physics at 3 GeV. In this way, it is possible to increase the energy of a storage ring although with a decrease in luminosity. Since the cross sections for electromagnetic and lepton final states are much larger than those for strongly interacting final states, one can still do physics in these channels. The reason such an increase in field is practical, is because an optimized design at 3 GeV seems to yield a relatively low magnetic field in the range of 6 to 9 kilogauss. I, therefore, think it is wise in the initial design of a storage ring to, at least, provide for such an increase in field at a future time.

IV. TECHNICAL DESIGN

A. Instability Limits on the Luminosity

I will consider only those factors which are specific to storage rings, and will not discuss the general problem of design of a magnet lattice. The most important problem is to attain the largest possible luminosity in the face of all the instabilities which have plagued storage rings up to now. These instabilities can be divided into two classes.

The first of these classes involves processes which lead to coherent motion of the whole beam. These kinds of instabilities have been observed and cured at many laboratories and will, I am sure, present no basic problem to the next generation of storage rings.

The second class of instabilities involves processes which lead to the apparent incoherent growth in the amplitude of betatron oscillations of particles within the beam.

We now understand this second class in terms of the generation of a series of closely spaced, high order, non-linear resonances by the non-linear impulse given to a particle in one beam as it passes through the non-uniform charge distribution of the other beam. The parameter which characterizes this instability is:

$$\Delta \nu = \frac{N_b \, r_e \, \beta_v}{2\pi \, \gamma ab}$$

where N_b is the total number of particles in a bunch, r_e is the classical electron radius, β_v is the orbit parameter of synchrotron theory and is the local value of betatron oscillation wave length, γ is the beam energy in unit of electron rest mass, and a and b are radial and vertical standard deviations of the gaussian charge distribution. $\Delta\nu$ is related to linear tune shift at the center of the gaussian bunch through the equation:

$$\cos 2\pi\nu' = \cos 2\pi\nu - 2\pi\Delta\nu \quad \sin 2\pi\nu$$

The experience at the Stanford 500 MeV electron storage ring, at Vepp-2 at Novosibirsk, and at ACO at Orsay shows that this parameter should be less than 0.025 if the beams are to be stable with respect to this incoherent blow-up.

If we adjust the transverse dimensions of the circulating beams so that they both have $\Delta\nu = 0.025$, the luminosity of the storage ring is then given by:

$$L = \frac{\gamma\Delta\nu}{2\beta_v r_e} \frac{I}{e} \cdot F$$

where I is the circulating beam currents in amperes, e is the charge of the electron, and F is a factor (near 1) which takes into account the bunch length of the beam. One sees from this formula that, at the instability limit for a given beam energy, the luminosity depends strongly only on the beam current I, and on β_v . Obviously the luminosity can be increased by increasing the available rf power, and hence increasing the beam current.

B. Small "Beta" Structures

Robinson and Voss of C. E. A. have recently shown that it is practical to reduce the value of beta by a large factor at the interaction region in a storage ring, and hence increase the luminosity, which can be obtained for a given circulating beam current. To stay within the incoherent instability limit, the cross sectional area of the beam must be adjusted to keep $\Delta\nu = 0.025$.

Figure 5 shows the magnet configuration and the beta function of a "small beta" insertion designed for the proposed SLAC 3-GeV storage ring, and illustrates some of the general features of small beta structures. While such an insertion looks to be very long at first glance, it is in fact not. All of the bending magnets and most of the quadrupoles would be required for a storage ring without the small beta insertion. The increase in circumference over a ring with moderately long Collins straight section for detection equipment, is about 10 meters per insertion for a 3-GeV design.

Figure 5 also shows the very rapid increase in beta, which occurs as one moves away from the point of minimum beta. In the central straight section of any small beta insertion, beta is given by:

$$\beta = \beta_0 \left[1 + \left(\frac{S}{\beta_0}\right)^2\right]$$

where β_0 is the minimum value of beta and S is the distance from the point of minimum beta. It is this increase in beta along the orbit which limits the extent to which beta can be reduced at the interaction point.

The limit arises as follows:

1° Tolerances on the alignment of magnets and on the quality of their field depend on beta at the location of the magnet. The large value of beta reached at the focusing elements close to the interaction region imposes increasing severe tolerances on these elements as beta at the interaction point is reduced.

2° Beta increases by a factor of two for a distance from the center of the interaction region equal to the minimum value of beta. The length of the circulating bunches of particles in the ring should not be very much longer than the minimum value of beta, since the incoherent instability limit depends on a weighted average of beta over the length of the interacting bunches.

3° The angular divergence of the beams at the interaction point increases as the minimum value of beta decreases. If this angular divergence becomes too large, it can become the limiting factor in the kinematic reconstruction of an event as seen in a magnetic detector and can prevent the separation and identification of different final states.

It appears practical to increase the luminosity of a storage ring by a factor of 50 to 100 by use of the low beta technique, over that which can be achieved at the instability limit by a conventional design.

The design of these insertions is not very complicated but it is tedious and so I will not go into detail here. It is possible to design such insertions so that they can be tuned and the value of β at the interaction point varied. In fact, they can be designed so that the change in the total number of betatron oscillations per turn is small enough when β is varied, so that β can be changed while a stored beam is in the ring. I think it will be generally true of high current storage rings that only the vertical β needs to be reduced. Reduction in radial β will decrease the beam area and can lead to values of the parameter $\Delta\nu$ greater than 0.025 for high current rings. For low current rings, the radial β should be reduced to the point where the value of $\Delta\nu = 0.025$ can be reached.

C. Choice of Operating Point

There is a clear choice of the operating point for a storage ring. The number of betatron oscillations between interaction points in an electron-positron storage ring should be close to, but above, an integer or half-interger. This choice is based on work by Bassetti which appeared in a Frascati report several years ago (LNF-135). Some of this work was also reported at the 1963 Dubna accelerator conference.

Bassetti's work has, I think, not received enough attention by designers of storage rings, except of course by the Frascati group. I confess that I didn't pay much attention to it until recently. Since this work is important and not generally known, I will spend some time describing it and its implications using a simple model.

We will represent the interaction of two beams by an effective thin lens at the interaction point. We take the case of one interaction point per turn, but the results also apply to more than one interaction point per turn if the betatron phase shift per turn is replaced by the betatron phase shift between interaction points.

The values of the betatron frequency and the function β in the presence of the beam-beam interaction are given by:

$$\cos 2\pi\nu' = \cos 2\pi\nu - \frac{\beta}{2f} \sin 2\pi\nu \tag{1}$$

$$\beta' \sin 2\pi\nu' = \beta \sin 2\pi\nu \tag{2}$$

where β and ν are the unperturbed values and β' and ν' are the values in the presence of the beam-beam interaction. The focal length of the equivalent thin lens which represents the interaction of the two beams is given by f, where f must be computed including the effect of the beam-beam interaction. In the simplest case, that of the thin ribbon beam:

$$f \propto h = h_0 \left(\frac{\beta'}{\beta}\right)^{\frac{1}{2}} \tag{3}$$

where h_0 is the unperturbed beam height. The equation for the tune shift can then be rewritten as:

$$\cos 2\pi\nu' = \cos 2\pi\nu - \frac{\beta}{2f_0} \left(\frac{\beta}{\beta'}\right)^{\frac{1}{2}} \sin 2\pi\nu \tag{4}$$

Changing variables to:

$$X = \frac{\beta}{4\pi f_0} \qquad ; \qquad Y = \left(\frac{\beta}{\beta'}\right)^{\frac{1}{2}}$$

we have the equation relating tune, changes in β and beam strength as follows:

$$\cos 2\pi\nu' = \cos 2\pi\nu - 2\pi XY \sin 2\pi\nu \qquad (5)$$

$$Y^2 = \sin 2\pi\nu' / \sin 2\pi\nu \qquad (6)$$

These equations have been solved by use of a computer with the beam strength X, and the initial tune ν as parameters. Some of the results of this calculation are shown in the next few figures.

Figure 6 shows the zero beam value of beta divided by the value of β in the presence of the beam-beam interaction, versus the number of betatron oscillations between beam interaction points (ν) minus the next lowest integer or half integer (n). The effect of the beam-beam interaction is to strongly reduce beta when operating just above an integer or half integer and to increase beta when operating just below an integer or half interger. This dynamic beta reduction near integral tunes can be used to increase the luminosity of a storage ring at the instability limit.

Figure 7 shows the change in betatron frequency ($\nu' - \nu$) versus $\nu - n$, for several values of the beam strength parameter X. The change in tune is smaller than X for small values of $\nu - n$ as one would expect from Eqs. (5) and (6). As $\nu - n$ increases, the change in tune increases, but the increase in β which occurs as $\nu - n$ approaches 1/2 from below decreases the effective beam strength and keeps the perturbed tune from ever reaching 1/2.

Figure 8 shows the relative luminosity per unit current versus $\nu - n$ for several values of the change in tune ($\nu' - \nu$). I have prepared this parameterization of the effect because I believe $\nu' - \nu$ is more nearly related to the incoherent instability limit than is the parameter X which has been previously used to characterize this limit. This belief is not completely a matter of faith. Rees has done some computer simulations of the interaction of beams in a storage ring which, I think, he will discuss later. These computer studies show that $\nu' - \nu$ very crudely does better characterize the limiting beam strength than does X.

The curves of Fig. 8 show an increasing relative luminosity as the unperturbed tune of the ring approaches an integer or half integer from above. The effect comes both from the decrease in β generated by the beam-beam interaction and from the increased beam strength allowed for a given tune change when working close to an integer. The curves are normalized to 1 for a beam strength of 0.025 and no change in β. Thus, the ordinate represents the luminosity relative to that which would be obtained if the beam strength parameter observed at both Stanford, ACO, and Novosibirsk (0.025) were used as the instability limit.

The stability of the solutions to the equations describing this dynamic effect on beta has been investigated by Dr. P. Morton of Stanford and myself using a perturbation technique. Equations (5) and (6) are actually coupled equations describing the mutual interaction of two beams. These equations are first solved assuming that the two beams behave identically. One beam is then perturbed (by changing its value of β for example) and the effect on the other beam is calculated. We then check to see if the change induced in the second beam reduces or increases the perturbation in the first beam. If the perturbation in the first beam increases, the solution is assumed to be unstable.

Figure 9 shows the boundary of the stable region in terms of the beam strength parameter X and the unperturbed tune of the ring. This boundary is above the limit which one would expect from the incoherent instability except at tunes just below an integer or half integer.

In actual practice it is not really clear how much of an increase in luminosity can be obtained from this dynamic β effect. A decrease in β at the interaction point is accompanied by an increase at other points in the ring guide field. The beams are not uniform ribbons, but are initially guassians in both radial and vertical dimensions. The focusing strength in a proper calculation should therefore be a function of amplitude, and the resultant β will also be a function of amplitude.

It is possible that because of these complicating factors, the full benefit to the luminosity of operation close to but above an integer or half integer will not be achieved. However, I do think it likely that some enhancement of the luminosity can be achieved. The other side of this coin indicates that one should avoid operation just below an integer or half integer tune. In this region, β will be increased and the luminosity reduced. In addition, beam strengths which are not precluded by other instabilities may make the beams unstable with respect to the dynamic beta effect.

D. The Long Range Instability

There is one possible instability about which I am still worried, and that is the so called "long range" instability. The impulse given to a particle as it passes through the other beam has its maximum non-linearity for a gaussian charge distribution, at a distance of 1 - 2 standard deviation from the center of the beam. We think now that non-linearities cause the incoherent instabilities, and these non-linearities can also cause instabilities for close passages of two beams. Such effects have been seen at the working storage rings. It is not necessary to bring two beams into exact alignment to cause the instability. It has been observed that the beams will blow up when their centers are still at some distance from each other. I do not know of any quantitative data on this effect, but all the laboratories have observed that very large beams will not cause instabilities when the separation between beam center lines is large, and will cause instabilities when the separation is small. This subject needs more work, but I think one can say now that small beam separations are very dangerous in a storage ring.

E. Vacuum

Most high current storage ring designs were provided in the past with a pumping system which was distributed throughout the ring, rather than one using localized pumps. I think that these distributed pumping systems are not really necessary. Everyone agrees that the desorbtion produced when synchrotron radiation strikes the walls of a vacuum chamber proceeds through a two-step process wherein the photons in the synchrotron radiation produce photo-electrons on the chamber walls, and these photo-electrons then cause desorbtion of gas molecules.

There has been a considerable amount of work in the last few years on the photo -electric process, praticularly in the Soviet Union. This work shows that the photo-electric yield is proportional to the reciprocal of the sine of the angle at which the synchrotron radiation strikes the metal surface. By suitably corrugating the surface of a radiation catcher, the synchrotron radiation may be made more normally incident and the photo-electric yield reduced. It has also been shown that the photo-electric yield from aluminum is a factor of two lower than from stainless steel. Combining these two effects yields a reduction in the estimated gas load by a conservative factor of 5 over past estimates which have been based on desorbtion measurements made in the Stanford 500-MeV storage ring. With this reduction in gas production, distributed pumping systems appear to be unnecessary in storage rings, except perhaps for those rings which have a small vacuum chamber aperture and hence a small chamber conductance.

F. Radiofrequency Systems

Storage rings have been designed with radiofrequency systems of relatively low frequency (30 to 50 MHz), and high frequency (300 to 500 MHz). Our studies at Stanford have shown that in the United States the cost of rf power is about twice as much per watt in the high frequency range, as it is in the low frequency range. This cost difference seems to arise from the higher cost of components and the low tube efficiency in the high frequency region. The only other advantage for low frequency rf over high frequency is that the feed-back systems to damp coherent beam instabilities are easier to build at low frequency. Some groups have designed storage rings which use existing synchrotrons with high frequency rf systems as injectors for their storage rings. In those cases, the problem of matching a storage ring rf frequency to the injector frequency so as to achieve optimum beam transfer, makes high rf frequency in the storage ring preferable.

With the use of low β sections in storage rings, two new factors must be considered. Since one of these two factors gives an advantage to high frequency rf, and the other to low frequency rf, the choice of frequency has not become any easier. The two factors are related to the bunch length and to the separation between bunches.

As we have noted previously, to take maximum advantage of a small value of β at the interaction point in a storage ring, the bunch length should not be much larger than the value of β. Since the bunch length is shorter for high frequency rf systems than for low frequency systems, the cost difference between high and low frequency is partly cancelled out if one measures costs per unit luminosity rather than per unit of rf power. On the other hand, the short distance between bunches in a high frequency system makes it extremely difficult to get large beam separations near the collision region. This may lead to very serious trouble with what I have called the long range incoherent instability.

V. SUMMARY

(1) The rates for strongly interacting final states are going to be very low at 3 GeV. They should be, according to the estimates I have given, about 10^{-5} to 10^{-6} of the lepton and γ- ray rates. The detectors should be designed to detect simultaneously as many of these strongly interacting final states as possible.

(2) A storage ring should be designed if possible, to take advantage of the maximum rf power at energies lower than its maximum design energy, in order to enhance the luminosity by increasing the beam current.

(3) Small β sections should be incorporated in any new design. It appears that the use of this technique can enhance the luminosity by a factor of 50 to 100.

(4) The operating point for storage rings should be chosen to be close to, but above an integer or a half integer, between interaction point. Since injection into a storage ring is most convenient near one quarter integral tunes, the best choice seems to me to design a storage ring in which injection is at the quarter integer, and where the ring can then be tuned with beam stored down towards an integer.

(5) More work is needed on the long range incoherent instability, but we can already conclude that small beam separations are bad.

(6) Distributed vacuum pumping does not seem to be required if arrangements are made to have the synchrotron radiation inside more normally to the vacuum chamber walls, and if aluminum is used for a radiation catcher.

(7) If the long range instabilities turn out to be no problem, there is no strong bias either for or against high or low frequency rf systems.

REFERENCES

1. Tollestrup et al., XIII International Conference on High Energy Physics, Berkeley (September 1966).
2. Conversi, Massam, Muller, and Zichichi, Nuovo Cimento 40, 690 (1965).
3. Akerlof, Ash, Berkelman, and Lichtenstein, Phys. Rev. Letters 16, 147(1966).
4. Nordberg and Kinsey, Phys. Letters 20, 692 (1966).
5. Chan, Chen, Dunning, Ramsey, Walker, and Wilson, Phys. Rev. 141, 1298 (1966); Phys. Rev. 147, 1174 (1966).

FIGURE CAPTIONS

1. The annihilation diagram in the electron-positron interaction which leads to the production of particle pairs.
2. Cross sections for proton-antiproton pair production.
3. Luminosity of the proposed SLAC 3 GeV storage ring.
4. Counting rate of proton-antiproton pair production for a ring with the luminosity of Fig. 3.
5. A small beta insertion giving β_v(min) of 5 cm. Q_{F_1} and the bending magnets are used to give a zero momentum vector in the central region. The use of three quadrupoles (Q_1-Q_3) allows β to be varied over a range of 4.5 cm. to about 2 meters.
6. Effect of beam-beam interaction on beta versus initial tune of a storage ring.
7. Change in tune due to the beam-beam interaction versus unperturbed tune, for several values of the beam strength parameter.
8. Relative luminosity per unit beam current versus unperturbed tune for several values of the shift in tune $(\nu' - \nu)$. The relative luminosity has been normalized to 1 at $X = 0.025$, $Y = 1$.
9. Stability of dynamic beta effect.

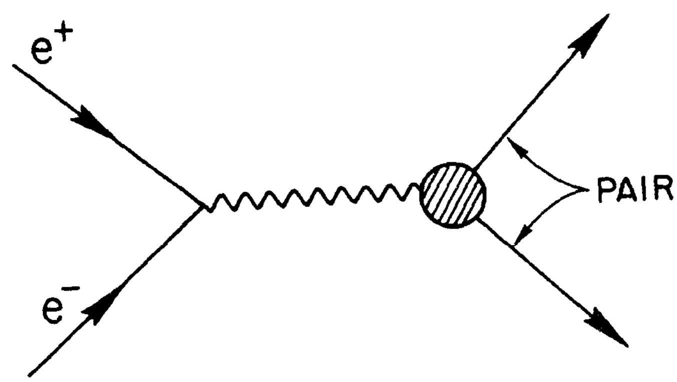
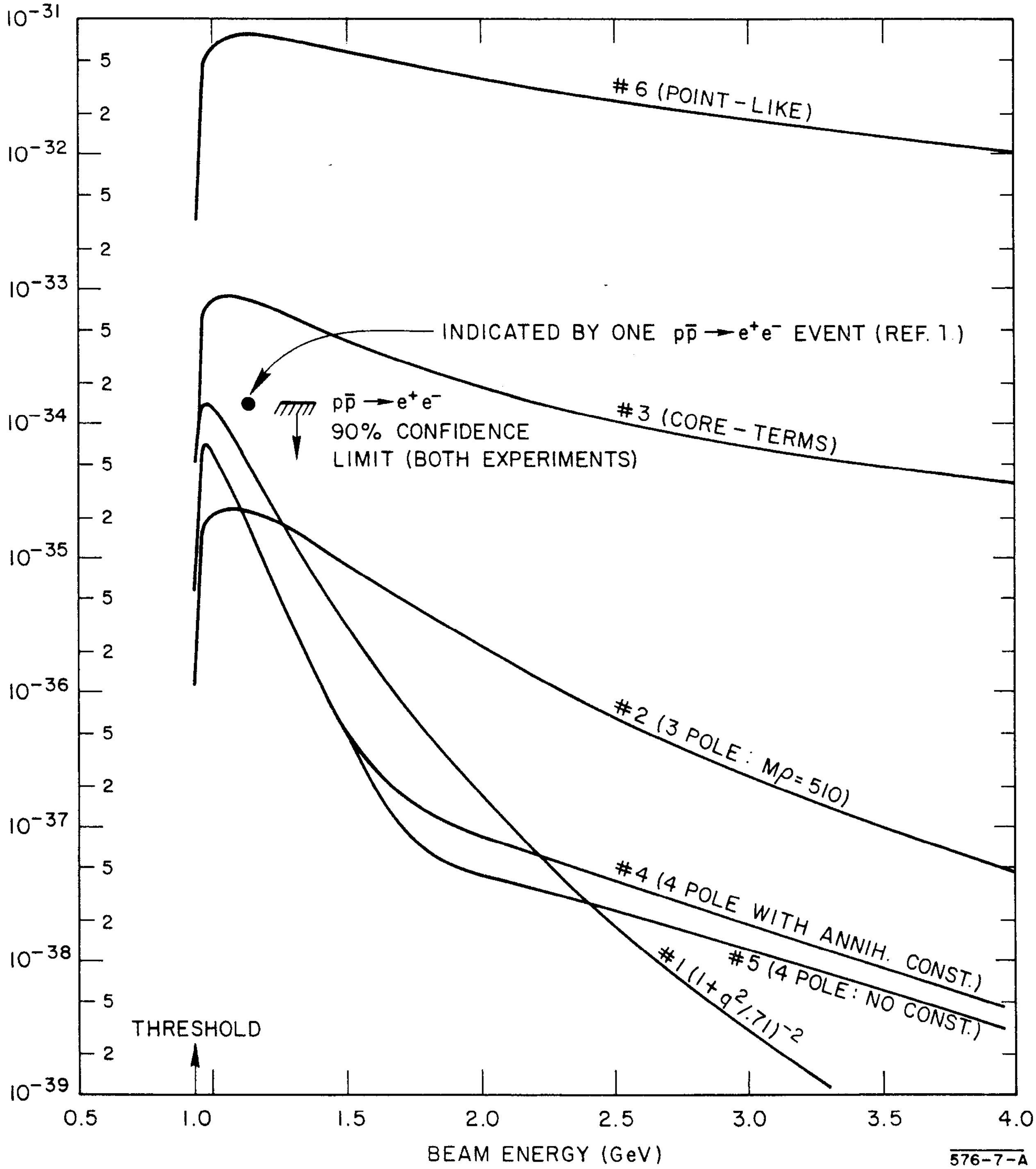
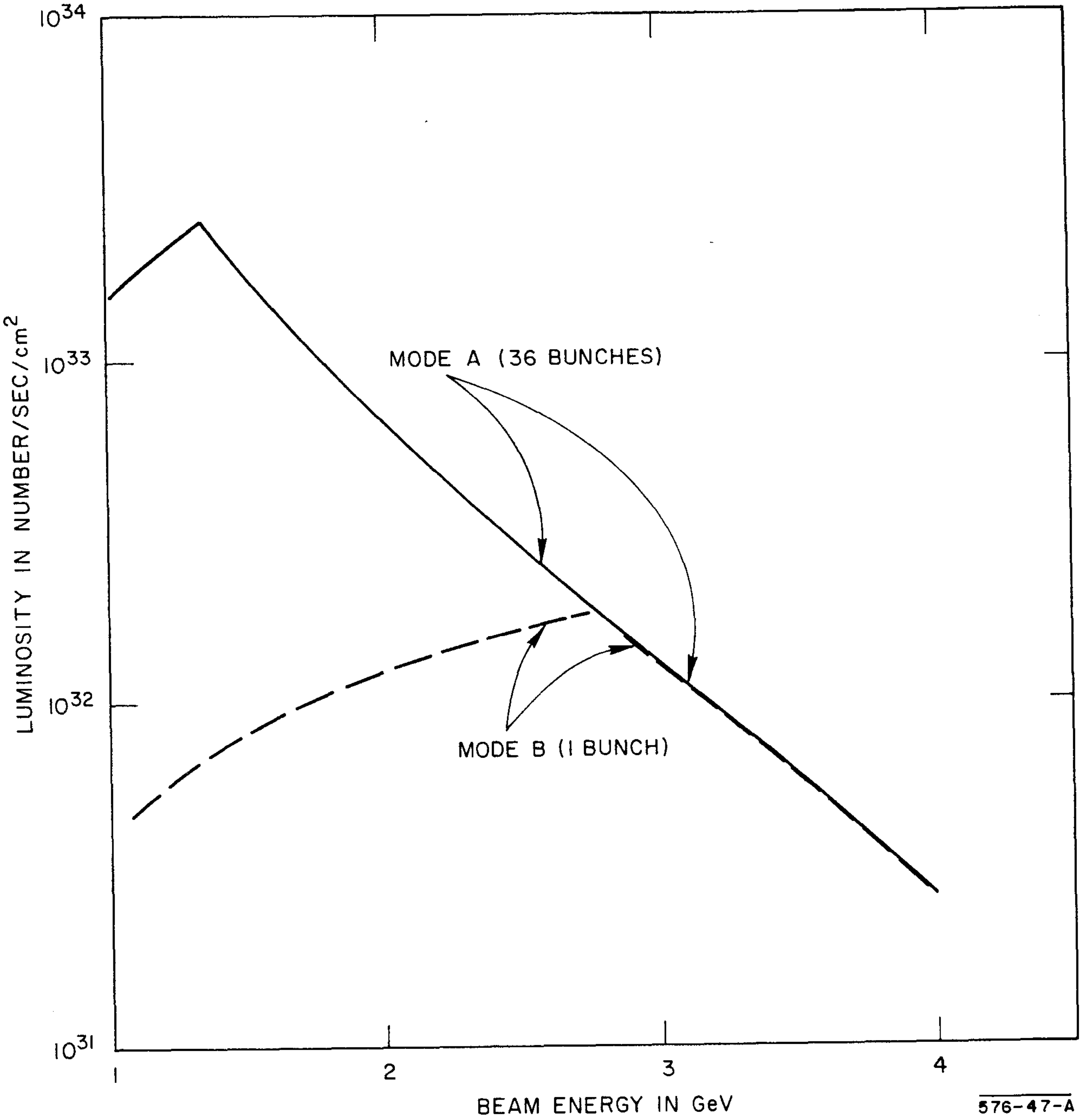


Fig. 1



10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
5
2
#6 (POINT-LIKE)
INDICATED BY ONE $p\bar{p} \rightarrow e^+e^-$ EVENT (REF. 1)
$p\bar{p} \rightarrow e^+e^-$
90% CONFIDENCE
LIMIT (BOTH EXPERIMENTS)
#3 (CORE-TERMS)
#2 (3 POLE: $M\rho$= 510)
#4 (4 POLE WITH ANNIH. CONST.)
#5 (4 POLE: NO CONST.)
#1 $(1+q^2/.71)^{-2}$
THRESHOLD
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
BEAM ENERGY (GeV)
576-7-A

Fig. 2



10^{34}
10^{33}
10^{32}
10^{31}
LUMINOSITY IN NUMBER/SEC/cm^2
MODE A (36 BUNCHES)
MODE B (1 BUNCH)
1
2
3
4
BEAM ENERGY IN GeV
576-47-A

Fig. 3

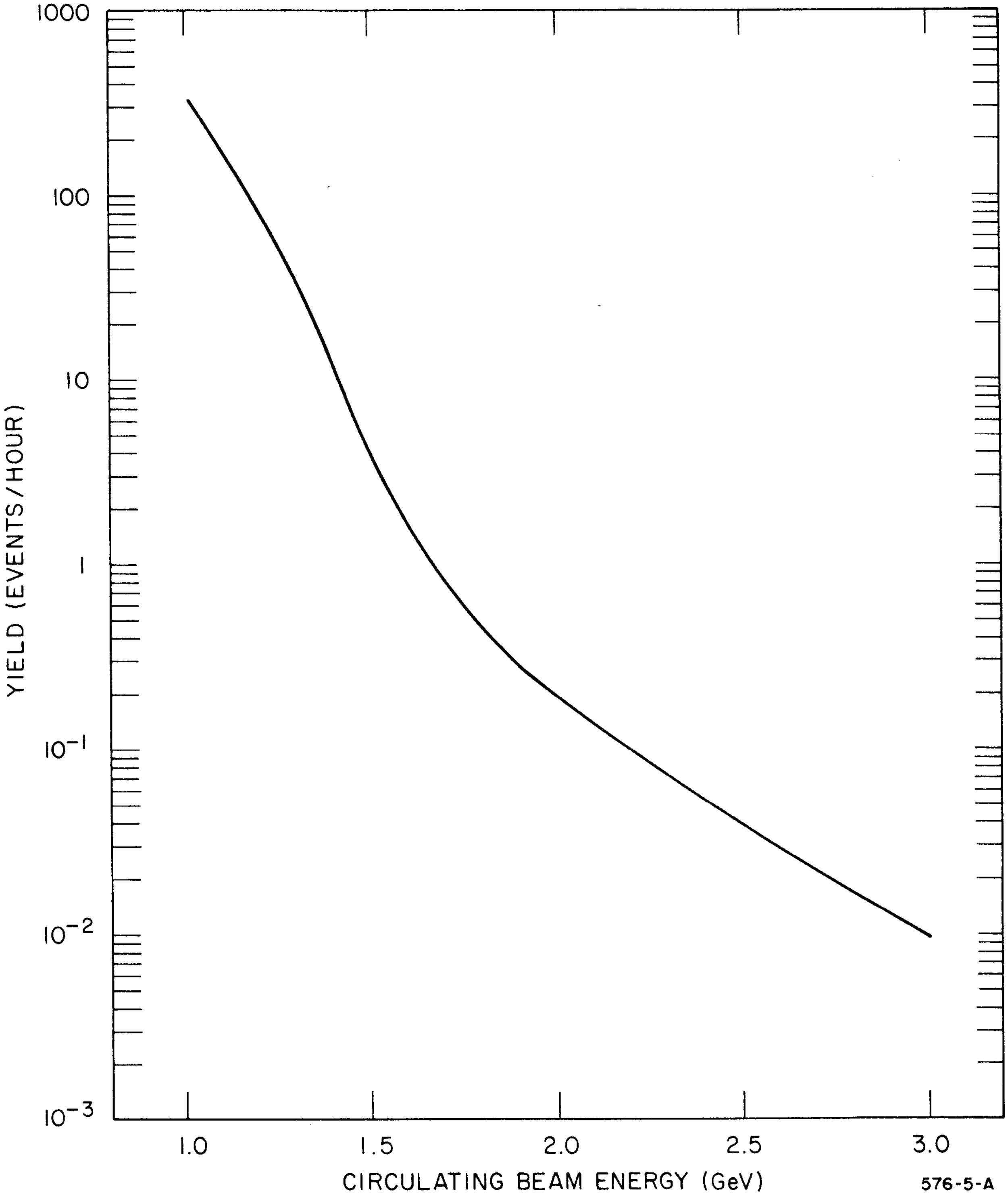
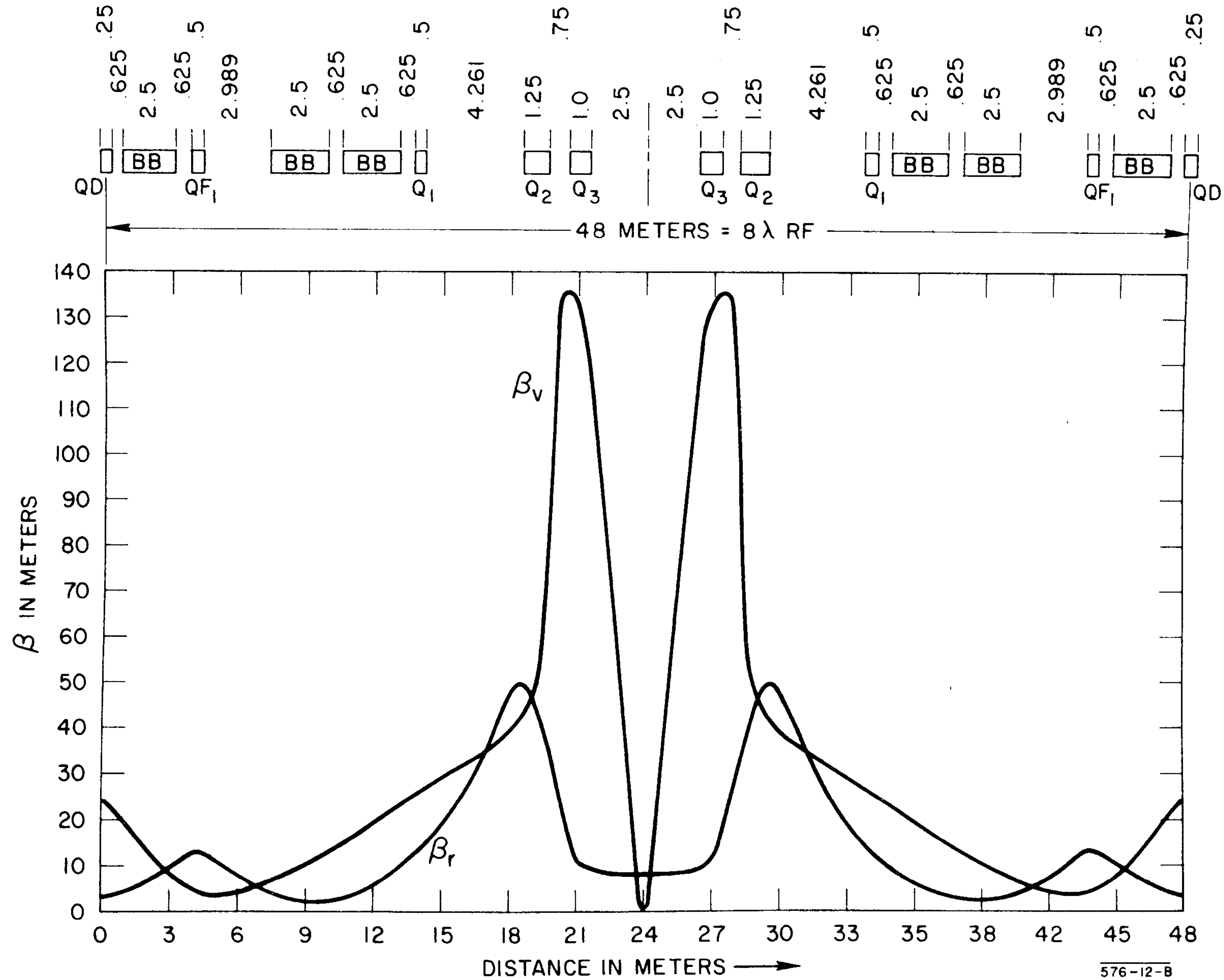

1000
100
10
1
10^{-1}
10^{-2}
10^{-3}
YIELD (EVENTS/HOUR)
1.0
1.5
2.0
2.5
3.0
CIRCULATING BEAM ENERGY (GeV)
576-5-A

Fig. 4



QD
BB
QF1
Q1
Q2
Q3
48 METERS = 8 λ RF
β IN METERS
βv
βr
DISTANCE IN METERS
576-12-B

Fig. 5

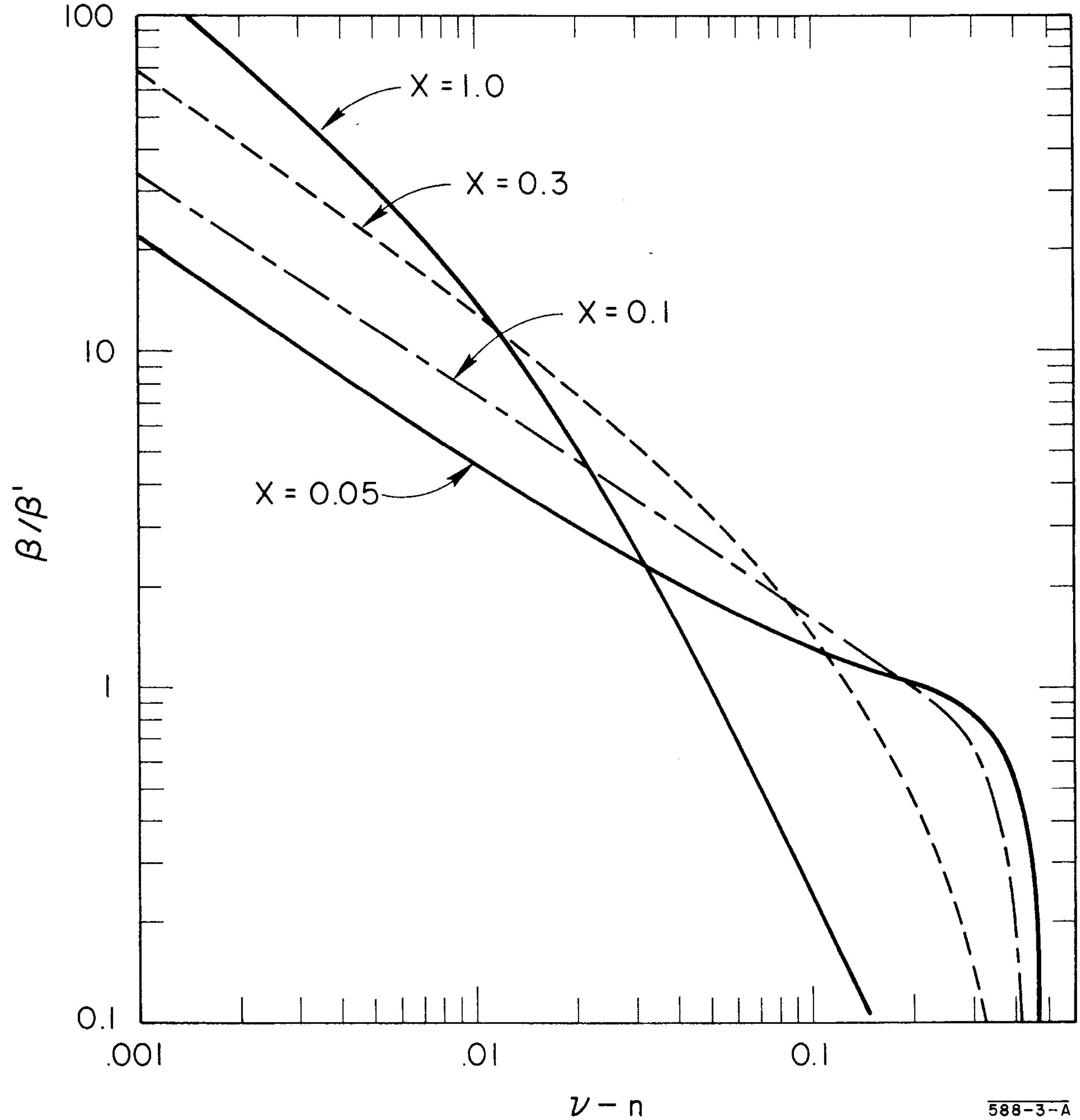


Fig. 6

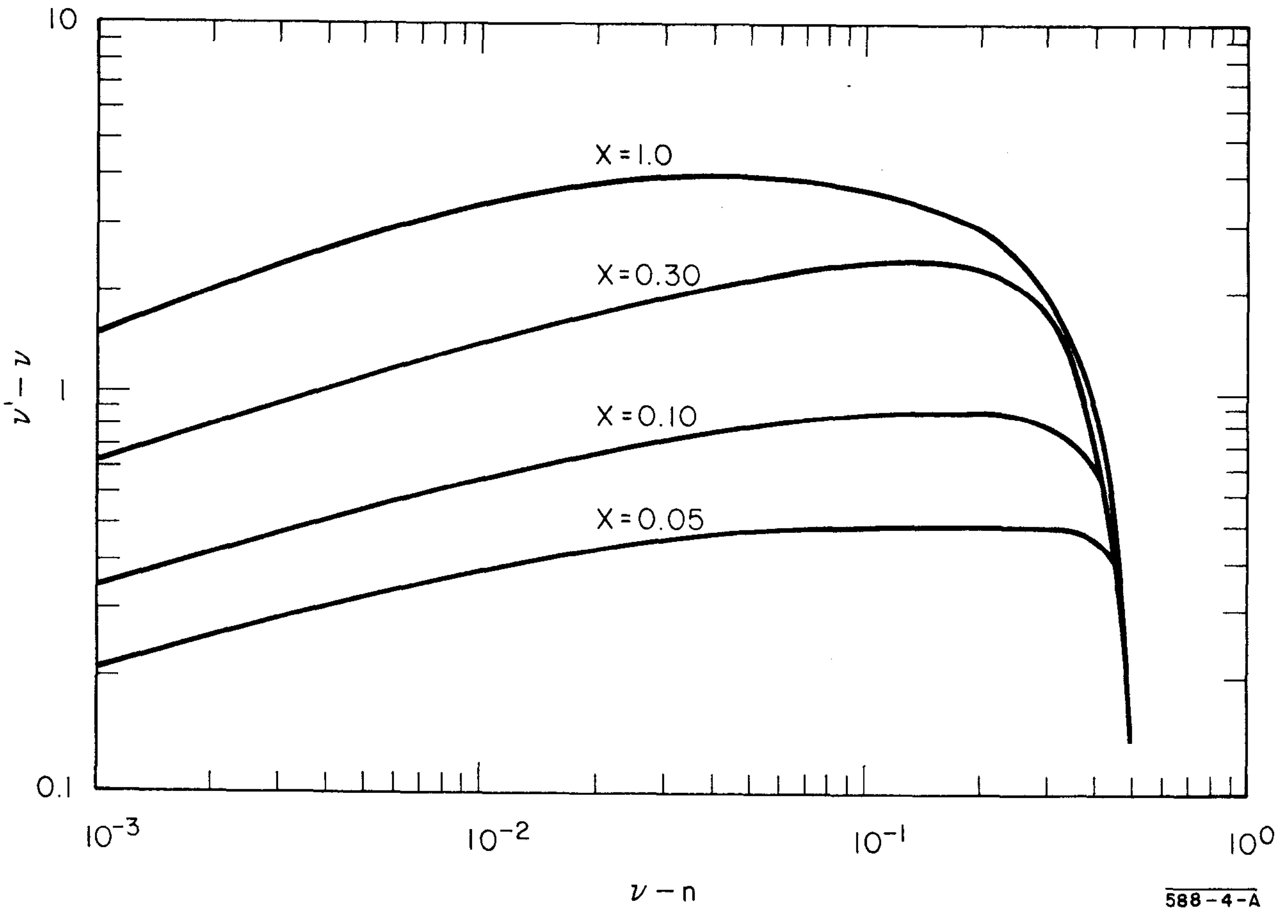


Fig. 7

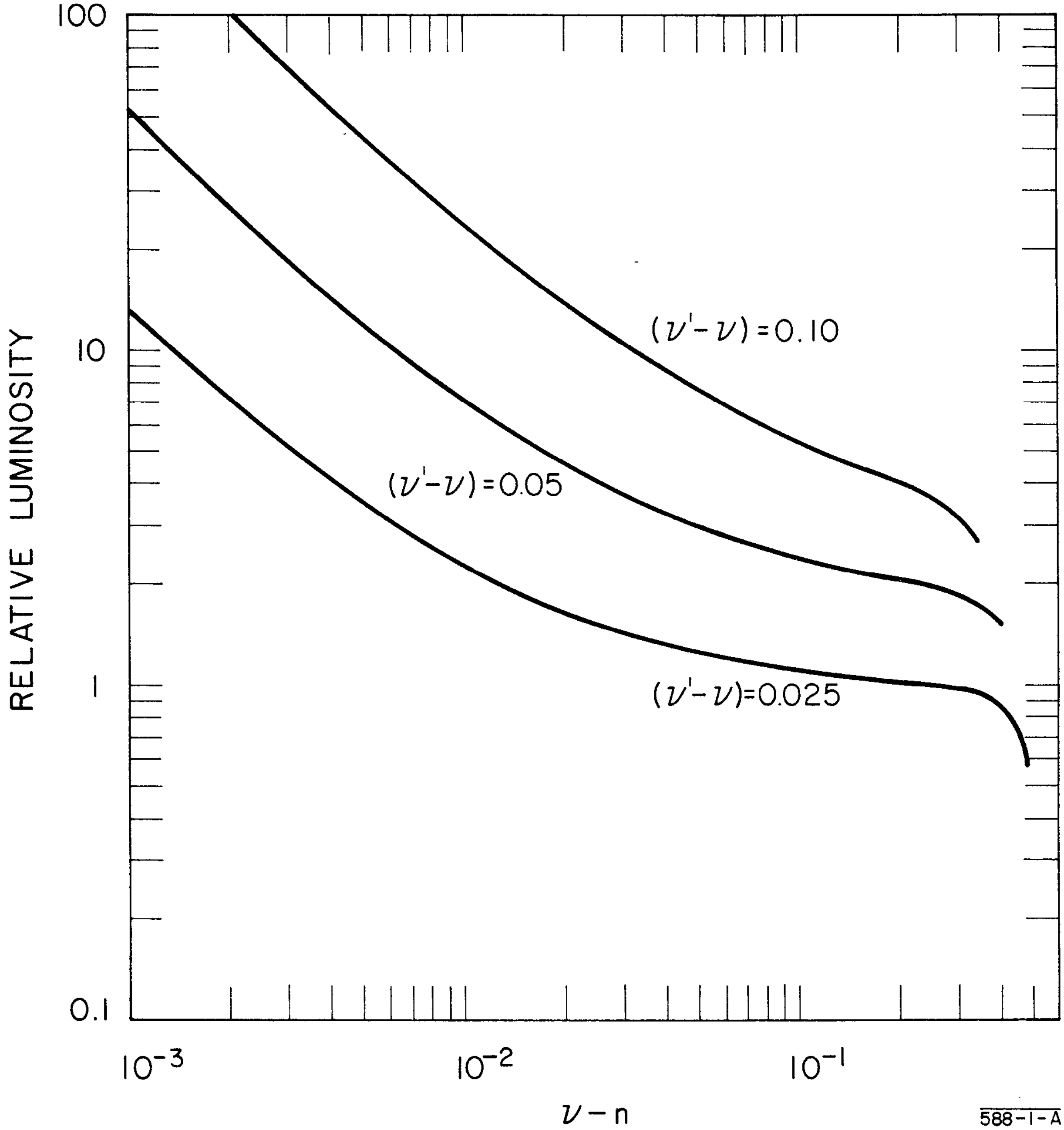

100
10
1
0.1
RELATIVE LUMINOSITY
$(\nu' - \nu) = 0.10$
$(\nu' - \nu) = 0.05$
$(\nu' - \nu) = 0.025$
10^{-3}
10^{-2}
10^{-1}
$\nu - n$
588-1-A

Fig. 8

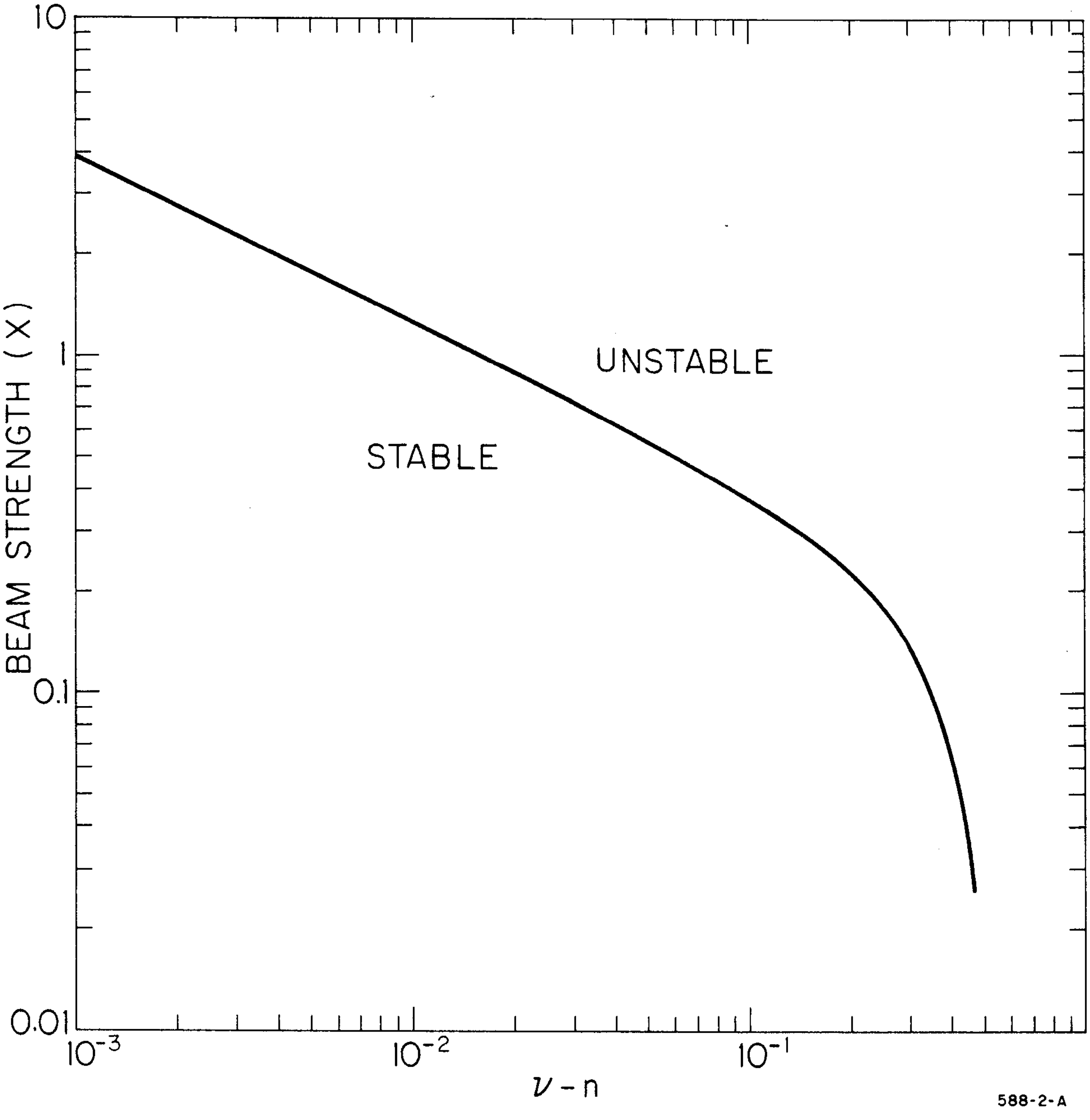

10
1
0.1
0.01
BEAM STRENGTH (X)
UNSTABLE
STABLE
10^{-3}
10^{-2}
10^{-1}
$\nu - n$
588-2-A

Fig. 9