CONCLUDING TALK - SEMINAR ON CRITICAL ISSUES IN DEVELOPMENT OF NEW LINEAR COLLIDERS*

WOLFGANG K. H. PANOFSKY

Stanford Linear Accelerator Center

Stanford University, Stanford, California, 94305

Presented at the Mini Symposium on Critical Issues in the
Development on New Linear Colliders, August 27-29, 1986
Madison, Wisconsin.

PHYSICS BACKGROUND

There have been many interesting developments during the past few years in respect to understanding the principles involved in the design of large linear colliders, but few of these developments deserve to be called conclusive. As is shown in Figure 1 the energy as measured in the basic constituent frame attained in past and projected colliders is still growing exponentially in time. However, the reason for the increased attention given to large linear colliders is, of course, the fact that the technologies of producing colliding beams in storage rings are becoming so expensive that devices beyond LEP and the SSC are not likely to be constructed, while new questions which can only be answered with energies attainable beyond those machines continue to be asked.

In general these discussions, and this summary is no exception, will measure the "reach into the unknown" of specific machines by their collision energy in the frame of the elementary constituents (i.e. quarks and gluons), and Fig. 1 has been so constructed. Therefore one tends to look at 2 TeV against 2 TeV or so electron-positron colliders, "equivalent" to the SSC. The physics goals of the SSC have been very extensively analyzed and presented; this is not the place for another recital. However there are a number of good reasons to look at other parameters, both more or less ambitious, as follows:

- The SSC is not as yet a reality, conversely the cost of a practical linear collider is wildly unknown at this time.

- The signal-to-background ratio for e^+/e^- collisions at the constituent energy equivalent to a hadron collider is greatly superior. Data analysis is much less burdensome. Reaction channels are more restricted; this leads to potential loss of some particular processes but greatly eases event discovery and identification.

- Practical lower energy e^+/e^- colliders in the charm, beauty and possibly top ranges can reach luminosities greatly in excess of those attainable with storage ring colliders.

- None of the energy thresholds for the new phenomena predicted to exist in the next energy range are quantitatively predicted.

For these reasons the design of e^+/e^- colliders over a wide range in energy and luminosity is important to examine.

LOGIC OF DEFINING PARAMETERS

The conventional logic concerning the design of electron-positron colliders goes something as follows: As new physical questions enter into view ever-increasing energies are required to answer them and the luminosity required to engage nature effectively demands that the luminosity increases in proportion to the square of that energy. Moreover, radiative effects in the electron-positron collision process should not be so large that the collision energy is greatly degenerated, or that the energy spectrum is unduly broadened. Thus the parameters E, L, and δ standing for Beam Energy, Luminosity, and Energy Width, respectively, are assumed to be specified by the customer-physicist. In addition one might assume that two other parameters, the β^* focusing parameter at the final interaction point and the invariant emittance ϵ_n be likewise defined by practical restrictions. Under these assumptions the orbit parameters of a linear collider, irrespective of the accelerating mechanism, can be defined if only one additional parameter is externally specified. If one chooses for that additional parameter the bunch length σ_z of the interacting particles, then the result in what up to now has been conventional theory defines the remaining parameters, in particular the average beam power, as represented in Figure 2. The reason for the shape of Figure 2 is that there appear two basic regimes defined by the so-called classical and quantum-mechanical regions of radiative beam-beam interaction. In the classical regime the radiation spectrum does not extend to photon energies beyond that of the primary beam and in the quantum-mechanical regime it has been assumed that the classical photon spectrum is simply cut off at the energy of the primary beam. Interestingly enough, no physical input is needed in the generation of these parameters beyond the relation for the total rate of radiation

3

of a charge in an electromagnetic field and the fact that the classical synchrotron radiation spectrum varies with the third root of the frequency.

Note that the dependent variable in Figure 2 is the power to luminosity ratio P/L divided by the square root of the invariant emittance times the β^* value at the interaction point. Thus independent tradeoffs among these four variables are of course possible. Note also that in principle this ratio can be minimized either at very low or very large values of the bunch length. There are, however, limits in the long pulse length direction both due to instabilities in case the beam-beam disruption parameter becomes too large or in case the bunch length becomes more than a small fraction of the wave length of the accelerating electromagnetic field. Based on these general considerations many authors have generated parameter tables for conceptual machines; Figure 3 shows such a table from a recent review by Loew. The highest energy example is clearly in the quantum mechanical regime of radiative beam-beam interaction.

If one wishes to consider the design of "factories" at lower energies for hadronic species composed of "heavy" quark states at luminosities well above those attainable for storage rings, then the limit is set by "disruption" in the beam-beam interaction. It does, however, seem possible to design machines at SPEAR energies up to $10^{33} cm^{-2} sec^{-1}$ energies at beam powers below one megawatt if normalized emittances in the 10^{-6} radian meters are achieved. B-factories are under extensive study.

The primary question we are facing today is whether the conventional wisdom outlined here is right. I can only answer this question today with a firm "maybe", hardly a satisfactory answer.

CURRENT UNCERTAINTIES

The role of the theory of beamstrahlung is crucial, in particular since the SLC will yield few data on the subject since the effect there will be both small and classical. Since that theory is in an unsettled state at present, there is a cloud over much of the systematic discussion of linear collider parameters.

No one calculation of electromagnetic effects in the beam-beam interaction is at this time firmly established outside the classical regime. Figure 2 is based on the simple cutoff considerations first introduced by Siegrist and Himel. These agree with the quantum-mechanical calculation of Ternov and Sokolov derived from the quantum-mechanical states of an electron in an extended electromagnetic field. These results have been brought into question by calculations of Drell and Blankenbecler which are currently in progress and which have been referenced by previous speakers. The principal reason why the new calculations appear to give a different – and smaller – radiative decrease in energy is that the longitudinal momentum transfer in the radiative process is so small that its corresponding wavelength can become large compared to the bunch length σ_z. Thus, the electromagnetic field in which radiation takes place is not infinite in extent as assumed by Ternov and Sokolov.

The implication of this uncertainty in analytical status is large. If, as is the current assumption, the beamstrahlung phenomenon is limiting the total number of electrons N which can be brought into interaction, then the scaling relationships for large linear colliders drive the designer towards shorter wave lengths. The reason is clear: The energy storage of an accelerating structure increases with the square of the wave length for a given gradient and total energy; if the number of electrons per bunch is limited, then the fraction of energy which can be extracted will decrease accordingly with increasing wavelengths. Since in a non-superconducting microwave structure the energy stored in that structure has to be dumped every pulse, this would result in decreasing power efficiency with increasing wavelengths. If, on the other hand, the energy broadening due to beamstrahlung is small and is only weakly dependent on the number of electrons per pulse, then this pressure towards shorter wave lengths would be greatly relieved and much of what we have come to believe about linear collider design would lose its validity. Palmer in his survey has dramatized the crucial role of beamstrahlung in his superchart (Figure 4).

Another issue which has not really been faced is the attainment of successful

interaction among beams of transverse dimensions in the angstrom range. We do not even know as yet how much trouble there will be in achieving systematically a successful interaction process in the SLC with its micron range diameter beams.

Successful attainment of such micro-beam interactions requires that four conditions be met:

1. Attainment of very low β^* values at interaction; good ideas have been introduced to produce such β^* values with either superdisruption multiple beam arrangements or with externally generated plasmas or laser beams.

2. A successful feedback mechanism to correct mis-steering of the beams. Such a mechanism requires precise sensing of the beam error followed by the application of suitable correction signals. For this feedback mechanism to work it is of course necessary that the sources of error remain consistent over a reasonable number of pulses. Thus noise which affects the radial position can prevent the feedback loop from being closed effectively. It is likely that a higher pulse repetition rate will ease this problem considerably, yet pulse repetition rate is a <u>dependent</u> variable flowing from the basic scaling considerations referred to above. The only real expectation of being able to design and construct a big linear collider with <u>very</u> high repetition rate would come from the successful attainment of a superconducting linac structure. More about this later.

3. All model calculations for a large linear collider require invariant emittances considerably smaller than those now planned for the SLC. This, in turn, establishes the need both for producing such small emittances and keeping them from growing. Producing small emittances, in particular for positrons, requires either damping rings of rather severe design or/and positron conversion schemes generating such a low emittance. Such schemes have been extensively discussed. Emittance growth seems to be dominated either by difficult to control non-linear radial fields or by the excitation of azimuthally asymmetric electromagnetic modes by the front of each bunch which dis-

torts its rear. Avoiding emittance growth generates extreme requirements for the coincidence of the electromagnetic axis of the accelerating structure and that of the external focusing or guiding system. Analysis of this problem leads to very severe alignment tolerances and to a requirement of absence of vibrations of the focusing elements at the submicron level.

4. Acceleration must be stable and consistent from pulse to pulse. This requirement sets tolerances on the performance of such hardware items as injection and ejection kickers, modulators, etc., etc. Moreover, the transverse momentum $\Delta p_\perp$ imparted at each stage of acceleration must be sufficiently small such that the stochastic addition of such impulses will not lead to an unacceptable final growth size. If $\Delta p_\parallel$ is the longitudinal momentum gain in each of the N accelerating stages, this implies that

$$\frac{\Delta p_\perp}{\Delta p_\parallel} < \left(\frac{N\epsilon_n}{\beta_a \gamma}\right)^{1/2}, \tag{1}$$

where β_a is the focussing function in the accelerator. Since γ/N is the energy gain $\Delta\gamma$ per independent accelerating stage this leads to the requirement

$$\frac{\Delta p_\perp}{\Delta p_\parallel} < \left(\frac{\epsilon_n}{\beta_a \Delta\gamma}\right)^{1/2} \tag{2}$$

Numerically for acceleration stages in the GeV range this leads to limits on the $\Delta p_\perp/\Delta p_\parallel$ ratio near 10^{-6} – a requirement difficult to attain even with a "hard" wall accelerating system, let alone with laser or plasma devices.

If the recalculation of the radiation loss during the beam-beam interaction in the high energy regime leads to a decrease in the estimate of radiative energy loss and to a decrease in the dependence of that loss on the bunch parameters, then the parametrization and scaling laws of the linear collider are dramatically changed. Let me emphasize that such a weak dependence would depend critically on the fact that the proportionality of the energy loss to the square of the number

of particles expected from a coherent radiation phenomenon is offset by the form factor inherent in the interaction. If I make the assumption that under the parameters of the machine in question, the beamstrahlung phenomenon is no longer controlling, then the limits on the number of particles per pulse are set by practical considerations. Specifically we can write for the power-luminosity ratio

$$\frac{P}{L} = 4\pi \frac{\epsilon_n \beta^*}{N} \left(mc^2\right) \tag{3}$$

In terms of the energy storage U in the accelerating structure this can be written as

$$\frac{P}{L} = \frac{4\pi \left(mc^2\right)^2 \epsilon_n \beta^* \gamma}{\eta U} \quad \text{where } \eta \text{ is the energy extraction efficiency.} \tag{4}$$

Note that U for a given particle energy is proportional to the gradient times the square of the wave length.

Thus the assumption of decreased dependence on beamstrahlung leads to the following conclusion:

1. The wave length should be long and the gradient as high as practical – quite the opposite of the current result.

2. A long wave length combined with a short bunch length would greatly ease the transverse wake instability, even if the number of particles becomes high.

3. However, as one increases the energy storage in the structure, the repetition rate would have to be decreased. At lower repetition rates the problem of achieving a successful beam-beam interaction becomes more severe because the pulse-to-pulse correlation making a closed feedback loop possible will become poor.

Thus the parametrization would not be defined by analytical properties of beam focussing, radiation, and acceleration, but by competition among the factors listed above. In other words, under these different assumptions the wave

length limit is set by practical considerations based on analysis of the irreducible noise terms due to a variety of factors such as seismic noise, man-made disturbances, power supply instabilities, RF source, "glitches", etc., etc.

Let me reemphasize that these remarks only relate to the TeV class machine where quantum-mechanical radiative effects come into play. The greater than SLC but well below one TeV machines will operate in the classical regime. Here, as we showed before, disruption between beams will be the limiting factor. Under these circumstances, as J. Rees has emphasized, the $\epsilon_n \beta^*$ product will scale as E^{-8} – a very severe practical barrier indeed.

ALTERNATE POWER SOURCES AND THEIR ECONOMY

Quite separately we have to consider the economic scaling of a linear collider which has been extensively considered by Palmer. This leads to the problem of RF power supply, among other factors. At this time general attention has focused on wave lengths in the 1-5 centimeter range, although the above considerations may reopen this question. The problem is how to build a radiofrequency system with its associated appurtenances which is "affordable." Most current analyses of the cost factors involved necessarily rest on an oversimplied basis; they are generally derived from simple scaling considerations based on unit costs of energy storage, of peak power, of average power, and of unit length. Unfortunately, from linear accelerator experience it is difficult to allocate costs in this simple manner without a specific conceptual design. For instance, when looking at the original costs of SLAC one finds that only 40% of the direct costs of the accelerator proper are associated with the primary components, that is the accelerator, the modulators, radiofrequency feed and klystrons. 43% is associated with "distributed systems," that is electrical, mechanical and control auxiliaries, and about 18% is associated with housing and control room. Thus a more detailed analysis of an actual system is necessary if one wishes to allocate costs to length proportional, power proportional, and energy storage proportional categories, as a physicist likes to do. Thus, although economic considerations are clearly controlling here

we cannot as yet reasonably compare the merits of different accelerating systems on an economic basis.

In a fundamental way all radiofrequency systems designed to feed linear colliders are 2-beam accelerators, that is they are transformers which convert energy from high current, low voltage systems into low current, high voltage electron beams. Figure 5 schematically tabulates such systems. In the conventional linac the high current beams are fractionated into a very large number of beams in individual klystron tubes, while optimistically the 2-beam accelerator schemes project a single beam running along the principal machine. However, all such long 2-beam accelerator schemes are beset by numerous instabilities and problems of harmonic growth which will require segmentation of the parallel beam structure to an as yet unknown extent. If the primary source is a "long electron beam" running parallel to the machine, then its energy can be extracted via free electron lasers or by extracting the appropriate harmonic from a tightly bunched beam by suitable output cavities. The beam can be bunched conventionally or be "born bunched" in a lasertron cathode. The energy of the driving beam can be replenished by induction units or by superconducting RF cavities operating at lower frequencies(Wolfgang Schnell).

The scheme whose transformer nature is most evident is the hollow beam arrangement of Weiland and Voss. Here that high current hollow beam travels on the outside of a disk-loaded structure with that disk-loaded structure serving directly as a transformer. This arrangement is just entering its experimental phase with the successful production of a hollow beam. Another "direct" transformer is the wakefield accelerator in which the electrons or positrons to be accelerated "ride the tail" of the intense electron bunch.

All the "long beam" schemes have limitations as to length to an as yet uncertain extent. The free electron laser arrangement, replenished by an induction unit (Sessler) may be unable to continue for long distances because of the problem of controlling the growth of side band power, although some remedies of this

10

problem are hopeful. The schemes involving production of tightly bunched beams suffer from the well-known beam breakup limits which have to be controlled by tight focusing, control of the impedance of surrounding structures and dispersion of parameters. In addition the head of each bunch will gradually erode due to interaction of the bunch with the external fields.

I tend to believe that the economic success of microwave sources suitable for linear colliders will depend on the successful attainment of radiofrequency sources which cover a considerable length. In looking at the cost of existing linear accelerator structures one is impressed by the dominance of the cost which derives from the fractionation of the power sources. For instance, at SLAC the modulators are more expensive than the klystrons and the modulators and klystrons combined are more expensive than the accelerating structure. Thus while decreasing the cost of accelerating structures through more "value engineered" manufacturing methods is desirable, this will be useful only provided the highly fractionated costs of the power sources are also substantially reduced.

As far as separate power sources are concerned there are many promising developments including the lasertron in which the traditional buncher cavity is replaced by a photocathode illuminated by radiofrequency modulated light. Then there is the recently developed Magnicon at Novosibirsk where the output cavity of the high efficiency sweeping beam gyrocon is replaced by a more conventional output cavity such that the spent beam can be more easily handled. There are several other tubes including the gyroklystron where magnetic fields are combined with conventional klystron principles. All of these show promise of higher peak powers at higher frequencies. The output of all these tubes can be further adapted to the requirements of linear colliders by pulse compression devices such as the one based on a "tree" of delay lines and directional couplers by Farkas. It is premature to judge which of these power sources will be most advantageous economically and whether their promised cost reduction will be sufficient. In fact, for the reasons cited, it is at this time even dubious whether the drive toward increased peak microwave power at higher frequencies is in the right direction.

SUPERCONDUCTING STRUCTURES?

The above remarks have focused entirely on traditional room temperature radiofrequency structures fed by a variety of power sources. Because of the difficulty of controlling radial forces and non-linearities I remain fairly pessimistic about the prospects for laser accelerators either of the beat wave type or the use of gratings or similar devices to convert the electromagnetic field of optical lasers into useful accelerating tools. Some of the other forms of plasma and wake schemes appear extremely difficult in practice. On the other hand, the recent improvements in superconducting cavities seem to indicate that an increased effort may be useful to examine whether superconducting structures might be suitable vehicles for large linear colliders.

There has been a great deal of recent progress in superconducting RF technology. Progress has been achieved through systematic elimination of surface defects leading to local heating and through the use of higher purity, and therefore larger heat conductivity, niobium. The result has been that superconducting cavities are now installed in several electron-positron storage rings and are being considered as energy replenishing drivers for 2-beam accelerators. Their use for linear colliders proper has been considered by Sundelin at Cornell, and by Amaldi and Langeler at CERN.

The problem involving superconducting linacs applied to colliders is first the limit of attainable gradient, and second the practical values of Q which are expected to be attained.

The theoretical limits on the gradient are set by the critical magnetic field H_c in superconductors as shown in Figure 6. This indicates that with niobium cavities the upper limit appears to be 60 MeV per meter, and even if niobium-tin cavities become practical 100 MeV per meter would be the limit. However, gradients below such limits should not be considered prohibitive. At 50 MeV/meter and assuming 0.5 watt/meter heat leak loss (which seems reasonable in view of SSC studies) a 1 TeV machine would lose 20 kilowatts at liquid helium tempera-

ture, requiring perhaps 20 MW of refrigeration power. Tunnel costs at \$500/ft. would be \$65 million and the cost of the cryogenic systems to make up for heat leak losses (SSC estimates) approximately equals that amount. Such costs are not prohibitive for a 1 TeV beam machine and therefore the wall losses are the dominant economic issue. The question is therefore one of Q. Quantitatively, a Q of about 10^{11} is needed to lead to wall losses not greatly in excess of the heat leak losses noted. There are no <u>theoretical</u> limits to the Q values at sufficiently low temperature. The practical surface resistance is the sum of a residual resistance R_o plus the theoretical BCS resistance which is given by

$$R_{BCS} \sim \left(\omega^2/T\right)^{-\alpha T_c/T} \tag{5}$$

where T_c is the critical temperature and where $\omega/2\pi$ is the frequency. This loss can be reduced indefinitely in principle by lowering the temperature; the rate of decrease in Q is more rapid than the loss of Carnot efficiency.

A great deal of progress has been made in recent times in reducing the residual resistance R_o which is presumably due to various forms of imperfection. Figure 7 indicates the practical values of Q which have been obtained and the predicted values of Q for the materials tabulated in Figure 6. Figure 8 shows that the Q only degenerates slowly with moderate gradients. Nevertheless, an order of magnitude improvement over current practice is needed if a CW superconducting machine is to become practical. It has recently been suggested that a compromise might be to operate a superconducting machine at, say, a 10% duty cycle. In that case the wall losses become acceptable even at current Q values but the stored energy will have to be thrown away at a low repetition rate as is the case in room temperature machines.

It should be noted that there are strong arguments to take superconducting machines seriously but these arguments go in exactly the opposite direction than those discussed previously in connection with room temperature machines. The biggest advantage is that one can consider very high pulse repetition rates and

thus the problem of closing the feedback loop as is required to steer the beams into collisions is greatly eased. In contrast to "warm" machines the number of particles per bunch then becomes small and the still open questions of radiative effects become irrelevant. The head-tail emittance growth problem becomes also trivial but the wake-field effects between bunches are significant but are very likely to be controllable by damping of higher modes. A substantial advantage is that the transfer efficiency of radiofrequency power to the beam is essentially 100%. The negative feature is that as the repetition rate increases while the number of particles per bunch decreases the beam diameters would have to shrink further if beam power is to remain constant. However, the beam brightness, that is the ratio of number of particles per unit of emittance would remain the same. Note also that since the efficiency of power transfer to the beam is very high for superconducting machines, higher average beam powers are apt to be affordable.

CONCLUSION

The principal conclusion from this limited overview is that most issues on linear colliders are still quite unsettled. It does appear that one should focus intensively on "conventional" metallic wall accelerator structures. Unless the recalculation of beamstrahlung substantially decreases the energy broadening due to radiative effects power sources and structures at wavelengths well below those now customary are indicated. If the recalculation revises the radiative effects downward, then it becomes much more difficult to parametrize the problem in a logical way. The limits are then defined by practical questions not as yet well explored, in particular the ones dealing with achieving successful collisions of angstrom size beams in the face of a practical noisy environment. Figure 9 illustrates the idea.

The basic issue – whether a linear collider at an energy matching that of the SSC in the sense of Figure 1 can be built at competitive cost – remains unanswered. On the other hand the opportunities at lower energies – candidates are factories for heavy quark hadrons – or an intermediate energy "classical"

14

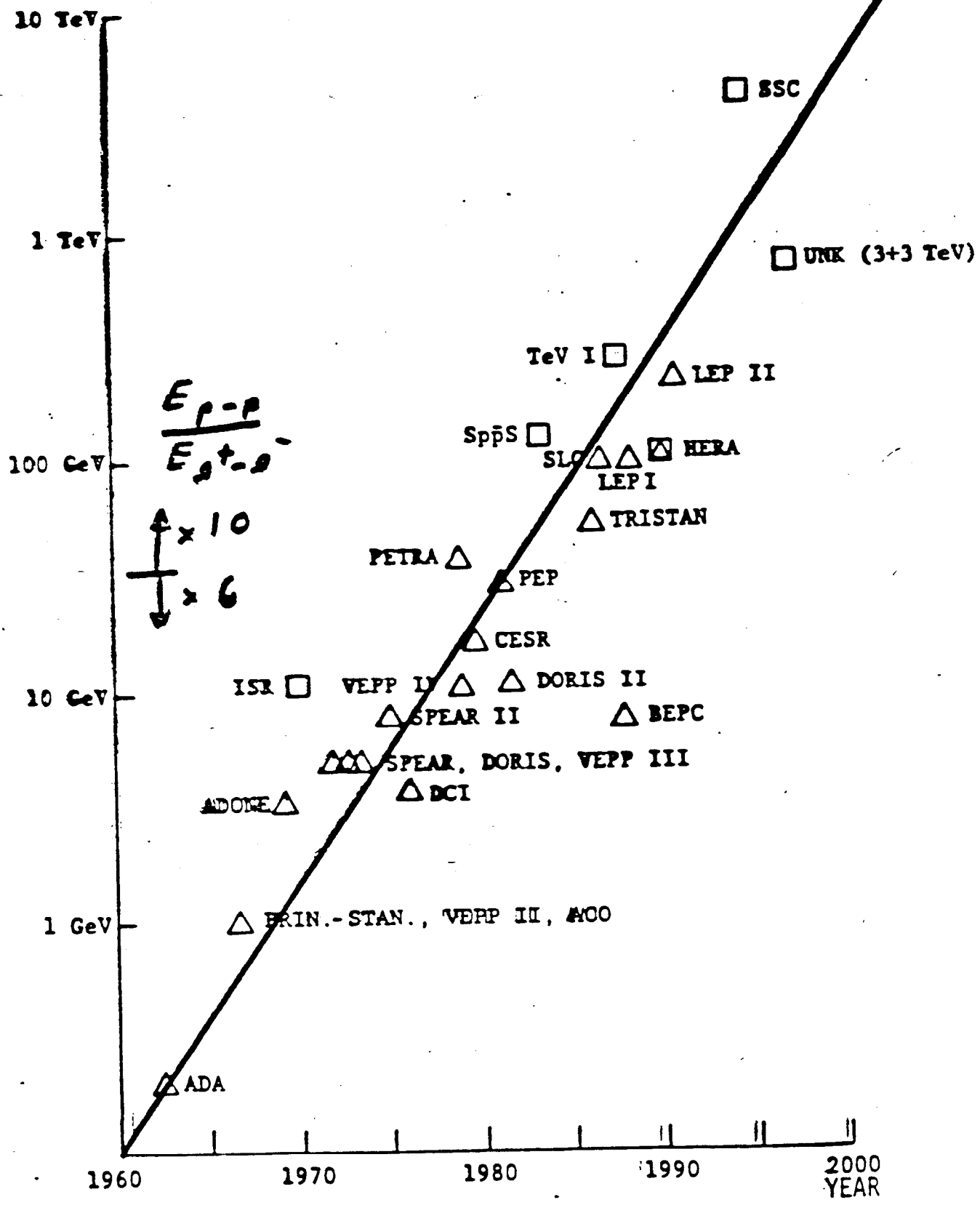post-LEP mchine are clearly feasible opportunities.

"CONCLUSION"

Aug 29, 1986
W. Laurofely

- Physics

- There is no Conclusion — yet

- Logic of Parameters for e^+/e^- Colliders

- Critical role of Beamstrahlung Theory

- Critical role of closing Feedback Li
at I.P. $\rightarrow$ rep. rate

- Power Sources $\rightarrow$ TBA/DISCRETE SOURCES

- Superconducting Structures

- Costs not yet meaningful

GROWTH OF PARTICLE COLLIDERS

Fig 1

- THE SSC IS NOT AS YET A REALITY, CONVERSELY THE COST OF A PRACTICAL LINEAR COLLIDER IS WILDLY UNKNOWN AT THIS TIME.

- THE SIGNAL-TO-BACKGROUND RATIO FOR E^+/E^- COLLISIONS AT THE CONSTITUENT ENERGY EQUIVALENT TO A HADRON COLLIDER IS GREATLY SUPERIOR. DATA ANALYSIS IS MUCH LESS BURDENSOME. REACTION CHANNELS ARE MORE RESTRICTED; THIS LEADS TO POTENTIAL LOSS OF SOME PARTICULAR PROCESSES BUT GREATLY EASES EVENT DISCOVERY AND IDENTIFICATION.

- PRACTICAL LOWER ENERGY E^+/E^- COLLIDERS IN THE CHARMONIUM, BEAUTONIUM AND POSSIBLY TOPONIUM RANGES CAN REACH LUMINOSITIES GREATLY IN EXCESS OF THOSE ATTAINABLE WITH STORAGE RING COLLIDERS.

- NONE OF THE ENERGY THRESHOLDS FOR THE NEW PHENOMENA PREDICTED TO EXIST IN THE NEXT ENERGY RANGE ARE QUANTITATIVELY PREDICTED.

Conventional Wisdom:

Specify E, δ, $\mathcal{L} \propto E^2$, $P_{Beam\ max}$
calculate N, f, ε_m, β^* as $f(G_2)$

Limits — Disruption
— "impractical" ε_m, $\sqrt{\varepsilon_n \beta^*}$, f

But:

δ - Calculation in doubt !

Problem

if $\delta \propto \dfrac{r_e^3 N^2}{\varepsilon_m \beta^* G_z} \times \left(\dfrac{E}{E_c}\right)^{4/3}$

Class. $\underline{\qquad\qquad\qquad}$ ↑ $\qquad$ ↑ $\qquad$ Q.M ,

N is limited by δ

if δ is weakly dependent on N,
  N is limited by **Energy** stored
  in accelerator

$$\frac{P}{\mathcal{L}\,(m_o c^2)\,(\varepsilon_m \beta^x)^{1/2}\, r_o} = \begin{cases} \dfrac{2}{3}\,\gamma\left(\dfrac{r_o}{\sigma_z \delta}\right)^{1/2} & \underline{\,<1_{\cdots}} \\[2em] \dfrac{8}{3}\,\alpha^2\left(\dfrac{\sigma_z}{r_o \delta^3}\right)^{1/2} & \underline{\,\textrm{G.}} \end{cases}$$

$$\frac{P}{\mathcal{L}\,(m_o c^2)\,f^x\,\gamma\,\varepsilon_m} = \frac{4\pi\,(m_o c^2)}{\eta U} \qquad \textrm{not } \delta-\textrm{limited}$$

Fig. 2

round beam ②
$\delta = 0.1$

P_{MW}

$L = \cdots \cdots = \pi \sqrt{3/2} \cdots$
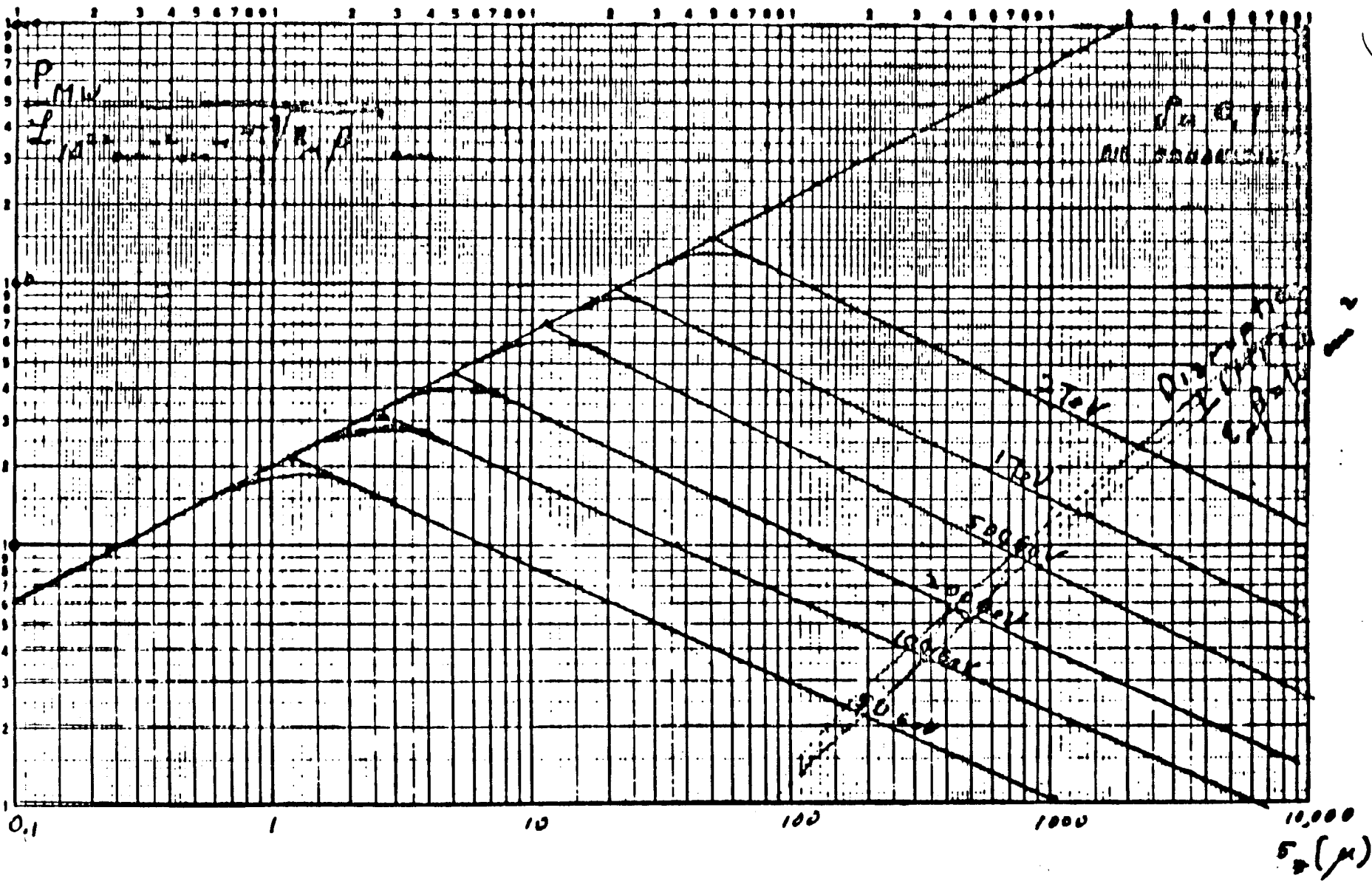
Examples of Beam Parameters for $E_{c.m.}$ of 0.1, 1 and 10 TeV

$E_{c.m.}$ (TeV)	0.1 (SLC)	1		10	
$\mathcal{L}$ (cm^{-2}sec^{-1})	2.4×10^{30}	2.4×10^{32}		2.4×10^{34}	
$\beta^{\cdot}$ (m)	7.5×10^{-3}	7.5×10^{-3}	10^{-3}	7.5×10^{-3}	10^{-3}
ϵ_n ($m_0 c - $m)	3×10^{-5}	1.5×10^{-6}	1.5×10^{-6}	10^{-8}	10^{-8}
$\epsilon_n \beta^{\cdot}$	2.25×10^{-7}	1.125×10^{-8}	1.5×10^{-9}	7.5×10^{-11}	10^{-11}
σ_r (μm)	1.5	0.1	0.038	2.7×10^{-3}	1×10^{-3}
$N(e^{\pm})$/bunch	5×10^{10}	10^{10}	2.4×10^9	2.4×10^9	8.8×10^8
σ_z (mm)	1	0.25	0.25	10^{-3}	10^{-3}
D	0.63	0.63	1.1	0.09	0.24
$H(D)$	1.5	1.5	4	1	1
δ	0.8×10^{-3}	0.266	0.3	0.3	0.3
$2P_B$ (MW)	0.144	3.6	0.760	14.7	5.38
$f_r b$	180	2300	2000	3800	3800
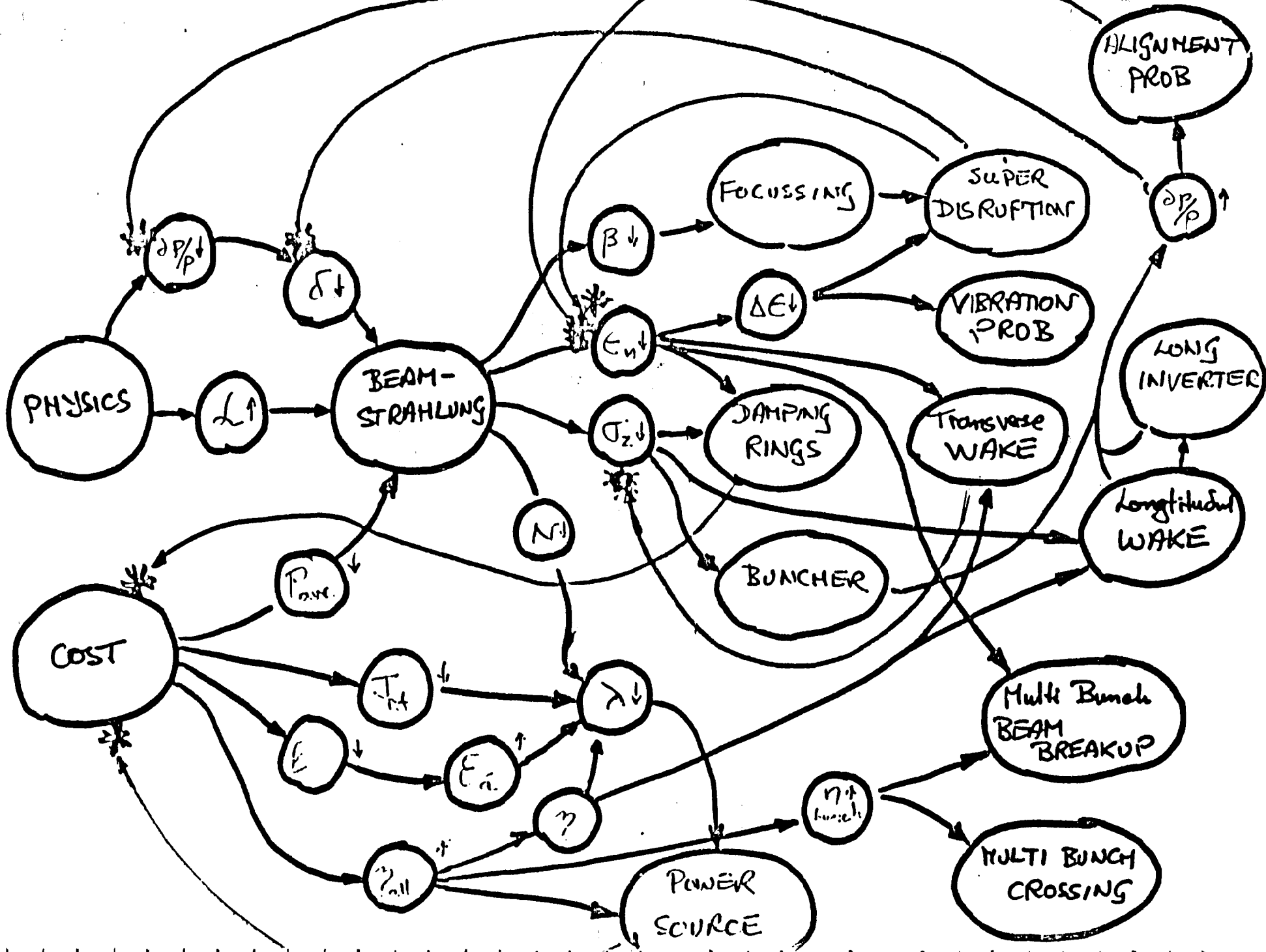
- Low β^* at IR
   Super disruption; Laser; external

- Feedback of Error Signal
   Noise $\longrightarrow$ limit on rep. rate

- Low initial ε_n
   Damping Rings; low ε_n e^+ converter

- Low ε_n growth

$$\Delta x < \sqrt{\beta^* \varepsilon_n / \gamma} \qquad \Delta x \sim N \, \omega^4 \left(\lambda/a\right)^{3.5} \left[\sigma_z / \varepsilon_n^{1/2}\right] d_{RM}$$

$$\underset{\text{"micro" } 10^{10}}{\uparrow \qquad \uparrow} \qquad \qquad \underset{.01\mu}{\uparrow}$$

- Section to Section Stability
   N Sections each contributing Δy

$$\frac{\Delta p_\perp}{\Delta p_{\parallel}} < \left(\frac{N \varepsilon_n}{\beta_a \gamma}\right)^{1/2} = \left(\frac{\varepsilon_n}{\beta_f \, \Delta y}\right)^{1/2}$$
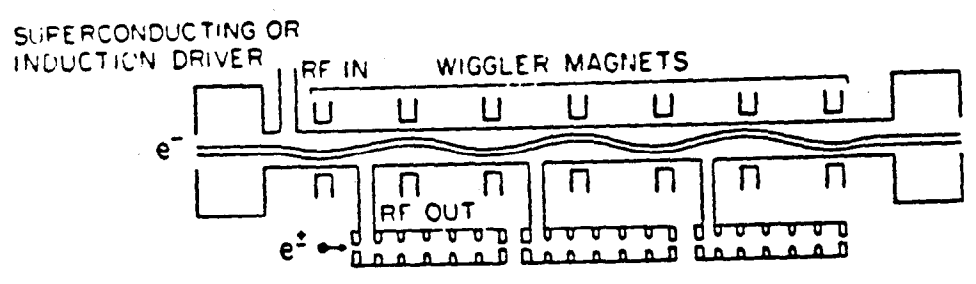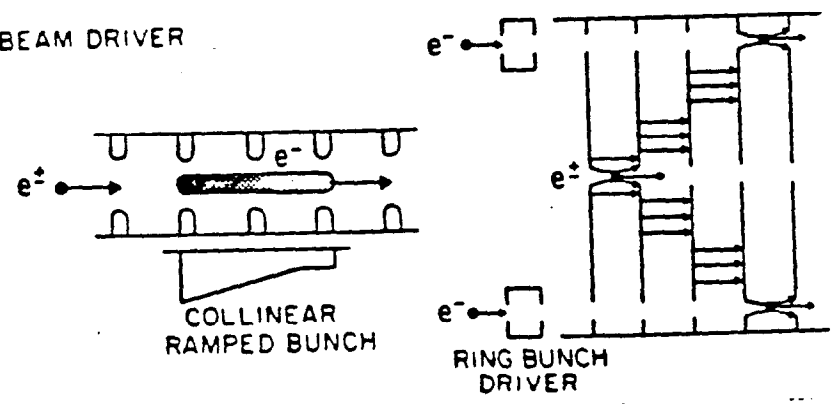
(a) "CONVENTIONAL" RF DRIVER

MODULATOR OR POWER SUPPLY

KLYSTRON GYROKLYSTRON LASERTRON

$n l_F$

ENERGY COMPRESSION

$e^{\pm}$

l_F

SUPERCONDUCTING or induction DRIVER
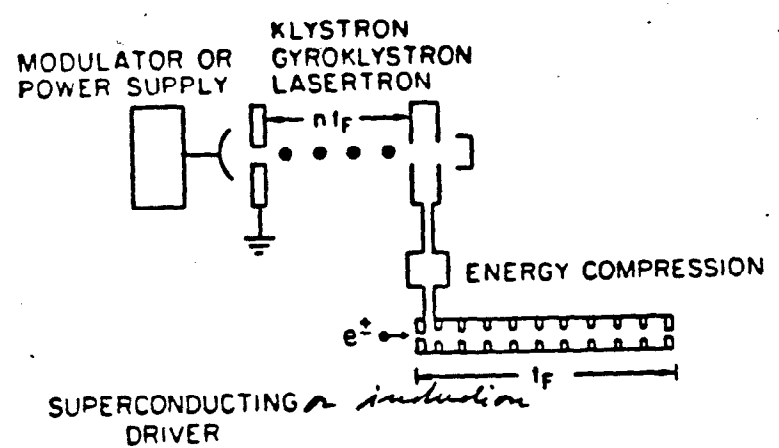
(b) "RELATIVISTIC" KLYSTRON DRIVER

e^{-}

$e^{\pm}$

SUPERCONDUCTING OR INDUCTION DRIVER

RF IN   WIGGLER MAGNETS

(c) FEL DRIVER

e^{-}

RF OUT

$e^{\pm}$
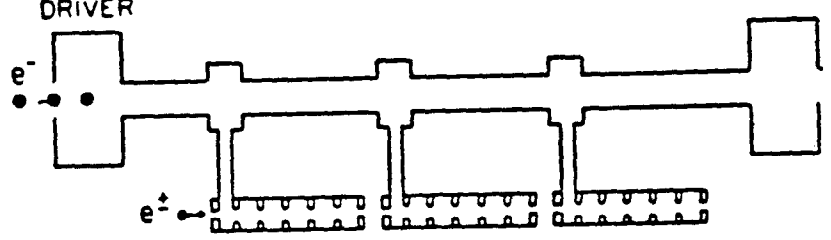
(d) COLLINEAR OR HOLLOW BEAM DRIVER

$e^{\pm}$ e^{-}

COLLINEAR RAMPED BUNCH

e^{-}

$e^{\pm}$

e^{-}

RING BUNCH DRIVER

2. BEAM ACCELERATORS

POWER SOURCE DRIVER	Induction	Super-cond. Cavities
∥ Beams FEL	Sessler et al.	Amaldi — Pellegrini
Relativistic Klystron	LBL/SLAC	Schnell
Co-axial Beams Hollow Beam	Weiland — Voss	
Wakefield Ramped Beam		

DISCRETE SOURCE
ACCELERATORS

<u>R.F.</u>

  Klystron
  Gyracon
  Magicon
  Gyroklystron
  Lasertron

$+$ Pulse Compression $\longrightarrow$ R.F LINAC

<u>PULSE</u>

SWITCHED POWER RADIAL TRANSMISSION LINE

MODULATOR

e^-
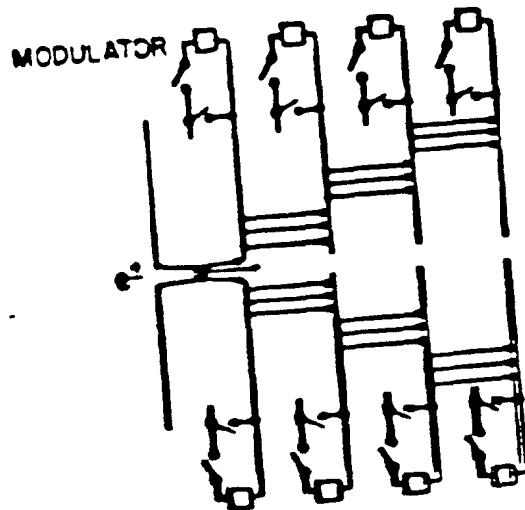
S-C Linear Collider

- **Gradient Limit** ~50 MeV,
  ∴ 40 km length for 1 TeV × 1 TeV

- **Heat Loss** ~0.5 W/m
  ∴ 20 kW at liq. He → 20 MW Power

- **Tunnel Cost** \$500/ft
  ∴ = 65 M

- **Q** $> 10''$

- **Wall Losses** $R_o + (\omega^2/T)e^{-\alpha T_c/T}$
  ∴ decrease R_o & increase T_c

Pro	Con
Higher Rep-rate	R&D needed on s.c. Materials
ε_m growth eased	Smaller beams
Higher $\eta_{R.F}$	Refrigeration Costs
Costs?	

Transition temperature and critical fields for a few superconductors

Material	Pb	Nb	$Nb_3 Sn$
T_c (K)	7.2	9.2	18.2
H_c (0) (Oe)	804	2000	5400
H_{sh} (0) (Oe)	1050	2400	4000
E^{sh}_{max} (MV/m)[a]	26.3	60	100
H_p (Oe)[b]	900	1590	1060

(a) For H_p/E_{acc} = 40 Oe/(MV/m). (b) Experimentally reached values.
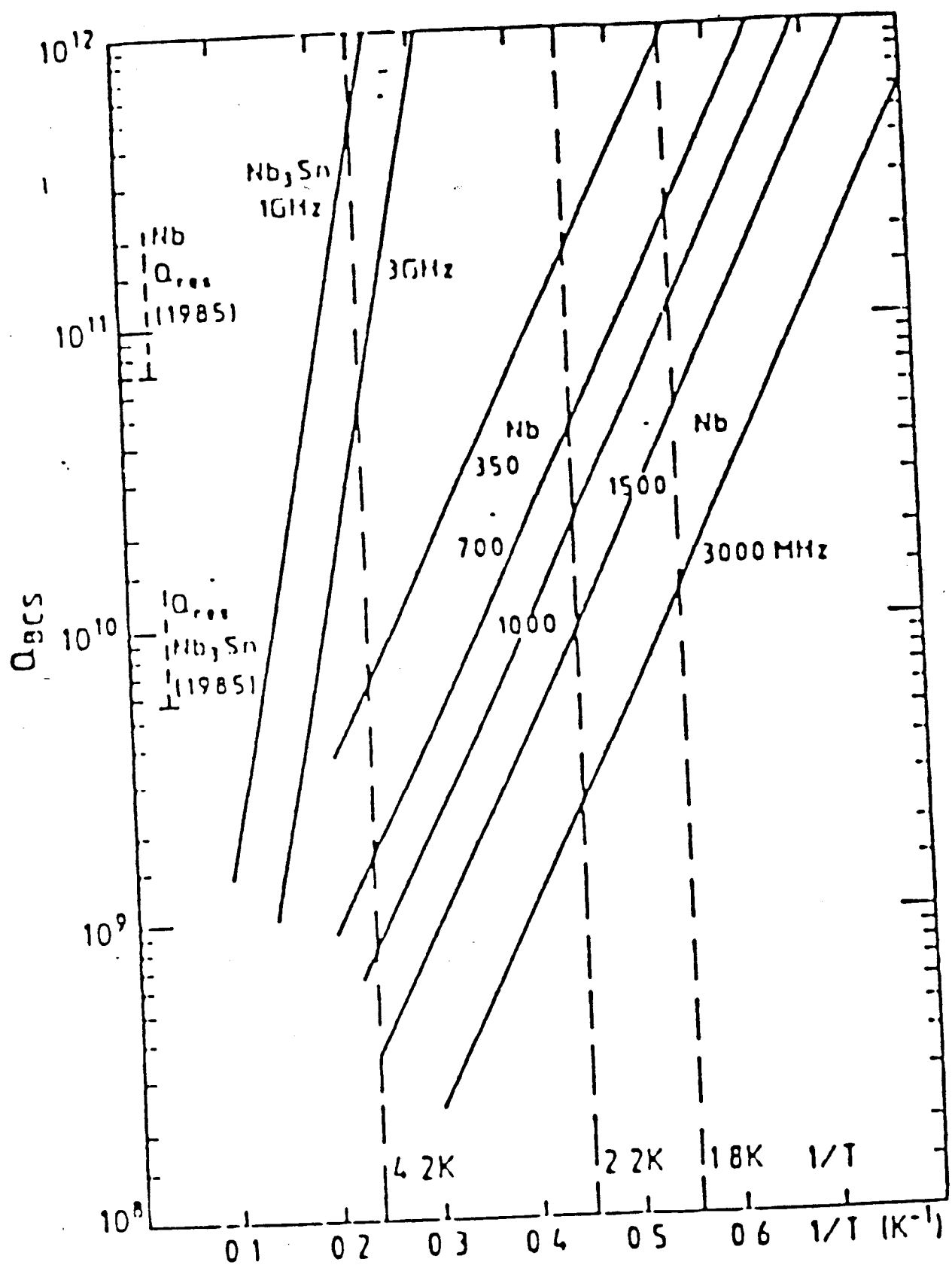
Theoretical quality factors (Q_{BCS}) for a typical accelerator cavity as a function of temperature and frequency. $Q = 280\ Ohm/R_s$ is assumed. The Q_{res} presently achieved are indicated.
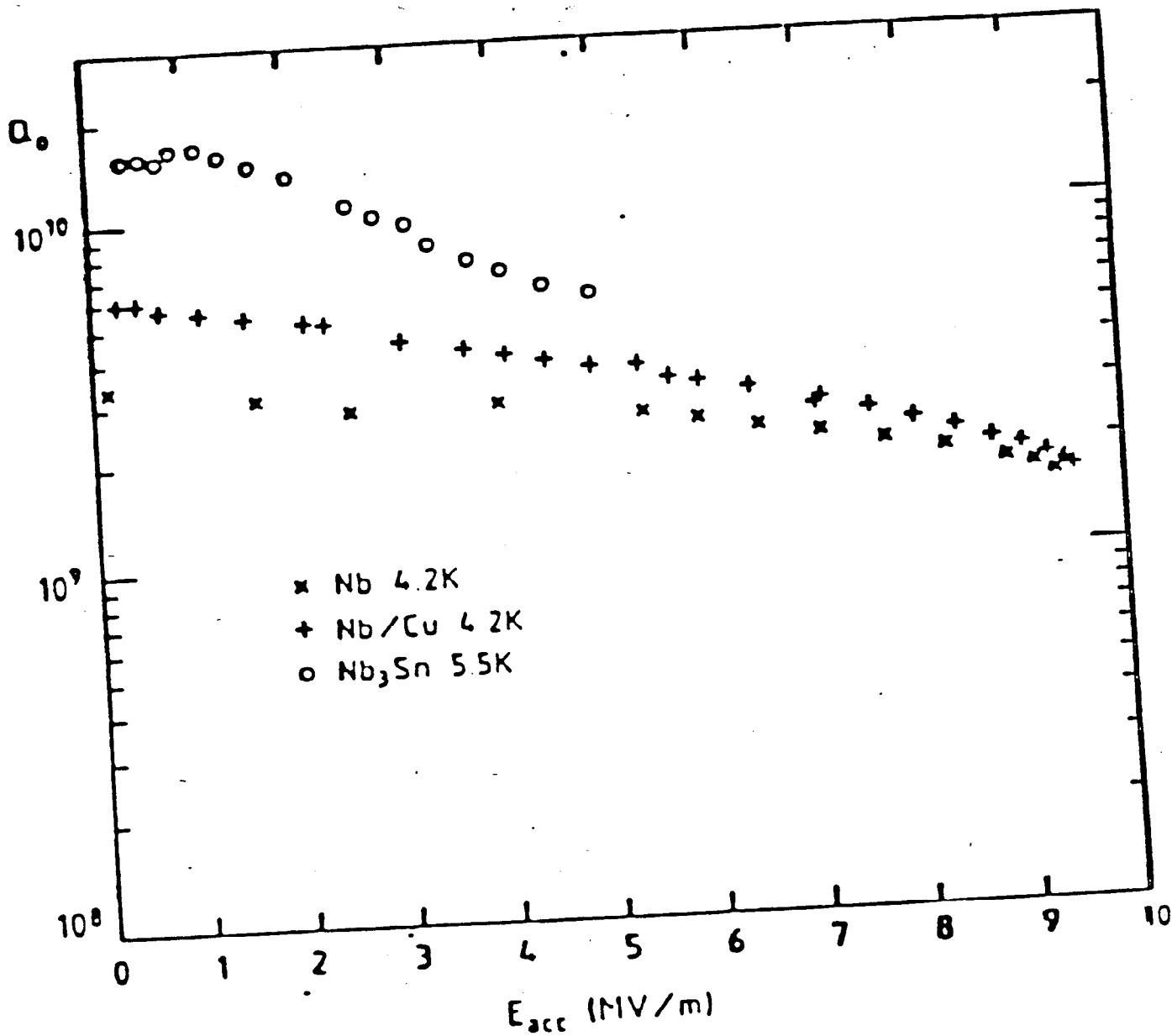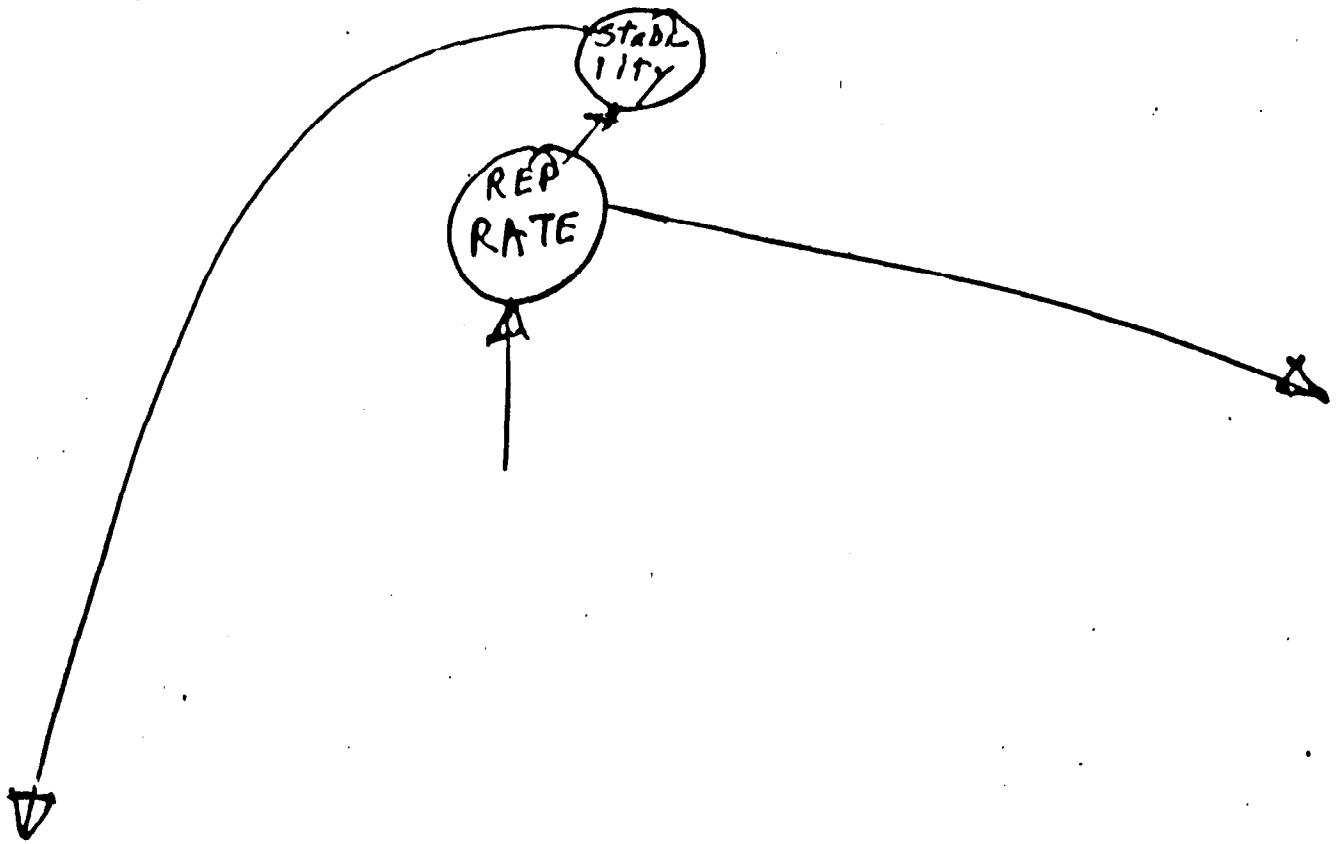
Fig. 8

Fig. 9

(b)