SLAC-PUB-2262
February 1979
(A)

PROPERTIES OF A LINAC-STORAGE RING STRETCHER SYSTEM*

G. A. Loew

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

This report will discuss some of the design characteristics and costs of a matched system comprising a pulsed linac and a storage ring to be used as a beam stretcher. The goal is to obtain a 2 GeV, 0.1 mA quasi-continuous stream of electrons. Within this goal, some optimization criteria will be examined and some technological difficulties will be indicated.

---

*Work supported by the Department of Energy under contract number EY-76-C-03-0515.

(Presented at the Conference on Future Possibilities for Electron Accelerators, University of Virginia, Charlottesville, VA
January 8-10, 1979.)

Introduction

A system consisting of a pulsed linac followed by a stretcher ring is one of several possible approaches to generate a 2 GeV, cw electron beam. Other methods such as superconducting or room-temperature cw linacs, cascaded microtrons and recirculating linacs were reviewed briefly in an earlier paper[1] and are being discussed in much greater detail by others at this conference. What is presented here is a first-order parameter study which attempts to obtain the optimum combination of a pulsed linac and a stretcher ring. Contrary to the usual situation which designers face, namely of already possessing a pulsed linac for which they want to extend the duty cycle by adding a stretcher, this study assumes total initial freedom of choice of parameters, constrained only by the availability of "reasonable" components and by costs. As will be seen, the optimization presented here is based on very approximate costs which are bound to change as a design is refined. However, most of the simple equations developed to conduct the optimization should still be generally valid.

System Design

Let us begin by assuming that we wish to obtain a continuous (or quasi-continuous) electron beam with a maximum energy of 2 GeV and a current of 0.1 mA. A simple schematic diagram of a possible system is shown in Fig. 1. It consists of a conventional pulsed linac followed by a transport system with a momentum-defining slit, a septum and a pulsed kicker to inject the beam into the storage ring. The ring itself contains conventional circular bends and straight sections where beam extraction can be accomplished by means of a wire septum. Details of the extraction method are discussed later.

The following assumptions are made about the system:

1) The electrons are accelerated in the linac up to the maximum energy, i.e., 2 GeV.

2) The linac beam is injected at this energy onto the closed equilibrium orbit of the ring for only a <u>single</u> turn (or actually slightly less to make allowance for the fall time of the kicker magnet). By limiting the injection to a single turn, one avoids the problems generally associated with displacing the orbit to prevent the returning beam from hitting the septum.

3) There is no RF system in the ring.

4) The time interval between injection pulses is set so that the energy loss of the stored beam due to synchrotron radiation from beginning of injection to end of extraction is k_1E, where k_1 is a small number of the order of a few percent.

5) The ring circumference is $2\pi pR$ where R is the magnetic radius and p is a packing factor, by definition always equal or

greater than one. From these assumptions, it is possible to derive the basic design equations of the system.

It is well known that in a storage ring the energy loss per turn due to synchrotron radiation is given by

$$U = \frac{CE^4}{R} \tag{1}$$

where $C = 8.85 \times 10^{-32}\ m(ev)^{-3}$. If the total energy decay allowed between injections is k_1E, then the total number of stored turns will be equal to k_1R/CE^3. Assuming that we use a conventional traveling-wave linac, the pulse length of the klystrons must be

$$t_{RF} = t_f + \frac{2\pi pR}{c} \tag{2}$$

where t_f is the filling time of the accelerator sections and c is the velocity of light. We see that the time between linac injections t_i must be equal to the number of stored turns multiplied by the going around time, namely,

$$t_i = \frac{k_1R}{CE^3} \times \frac{2\pi pR}{c} \quad . \tag{3}$$

The linac repetition rate is then the reciprocal of t_i:

$$n_{pps} = \frac{cCE^3}{2\pi pk_1R^2} \tag{4}$$

and the linac RF duty cycle is given by

$$D_{RF} = (t_f + \frac{2\pi pR}{c}) \frac{cCE^3}{2\pi pk_1R^2} \tag{5}$$

If we assume that the ultimate cw current at the output of the system is i_{cw}, then the required linac peak current to be injected in a single turn and to be extracted uniformly over k_1R/CE^3 turns is

$$i_{pk} = i_{cw} \frac{k_1R}{CE^3} \tag{6}$$

Let us now assume that the pulsed linac is of the constant-gradient type. The energy per section is given by[2]

$$E_1 = (1 - e^{-2\tau})^{\frac{1}{2}} (P\ell r)^{\frac{1}{2}} - i_{pk} \frac{r\ell}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right) \qquad (7)$$

where P is the peak power per feed, τ is the attenuation per section, ℓ is the section length and r is the shunt impedance per unit length. For simplicity the RF power lost in the waveguide feed to the accelerator section will be neglected in what follows. The number of required accelerator sections would simply be E/E_1 but we shall assume for the sake of redundancy that there will always be two inactive klystrons and linac sections in reserve. Then, the number of active linac sections on line is given by

$$N = \frac{E + 2\, i_{pk} \frac{r\ell}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right)}{E_1} \qquad (8)$$

The RF-to-beam power conversion efficiency is given by

$$\eta = \frac{i_{cw} E}{NPD_{RF}} \qquad (9)$$

The total length of the linac, assuming 20% extra space for beam guidance magnets and instrumentation, is given by

$$L = 1.2\,(N + 2)\,\ell \qquad (10)$$

and the energy loss due to beam loading by

$$\Delta E_B = (N + 2) \frac{r\ell}{2} i_{pk} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}}\right) \qquad (11)$$

The AC power for the linac is simply

$$P_{AC} = \alpha N P D_{RF} \qquad (12)$$

where α is the combined klystron-modulator efficiency.

To proceed, we shall now narrow down the choice of parameters and assume, because of the ready availability of components at S-beam, that the linac is built at the SLAC frequency, namely 2856 MHz. Let the peak klystron power be 36 MW peak (the latest SLAC klystrons produce 38 MW) and the typical attainable Q in the accelerator sections be 13,000. Let us further assume a 20% reserve in current to make up for possible losses in the momentum analyzing slits of the linac and the injection and extraction systems of the stretcher, leading to a value $i_{cw} = 1.2 \times 10^{-4}$ A. Let $k_1 = 2 \times 10^{-2}$ and $p = 1.8$: these numbers are believed to be reasonable for a practical storage ring design. As to the linac sections, let us explore four different possibilities as listed below:

1) $\ell = 3\,\text{m}, \quad \tau = 0.57, \quad r = 57\ \frac{\text{M}\Omega}{\text{m}}$

2) $\ell = 4.5\,\text{m}, \quad \tau = 0.85, \quad r = 57\ \frac{\text{M}\Omega}{\text{m}}$

3) $\ell = 6\,\text{m}, \quad \tau = 1.14, \quad r = 57\ \frac{\text{M}\Omega}{\text{m}}$

4) $\ell = 3\,\text{m}, \quad \tau = 0.30, \quad r = 57\ \frac{\text{M}\Omega}{\text{m}}$

with $t_f = \frac{2Q}{\omega}\tau$

The first is the SLAC design and the other three are variations thereof.

Using the above values, it is now possible to plot all the major system parameters as a function of the stretcher magnetic radius R. All plots are shown, where applicable, for the four different types of accelerator sections chosen. Fig. 2 shows the required linac RF duty cycle and Fig. 3 the corresponding repetition rate. Notice the $1/R^2$ dependence as predicted. The required linac peak current is shown in Fig. 4: it is linear with R and independent of what kind of linac section is used. Fig. 5 gives the number of active klystrons and linac sections and Fig. 6 gives the resulting length. Steady-state beam loading is shown in Fig. 7 and the RF-to-beam power conversion efficiency in Fig. 8. Finally, the linac AC power is given in Fig. 9, assuming the combined klystron-modulator efficiency α to be 0.5.

System Costs

Looking at these results, we see that acceptable designs can in principle be found over a fairly wide range of values of R. To narrow down this range, we must consider the constraints imposed by the availability of suitable components and their total cost. An accurate cost study of the system as a whole would of course require a detailed design of the linac and the ring, which is beyond the scope of this paper. However, to get a rough estimate, we can use some very approximate expressions for sub-systems costs, based on common experience. The following expressions are assumed in what follows (all numbers are in millions of dollars):

Total cost of linac power components: $C_P = 0.1\,(N+2)\,D_{RF} \times 10^3$

Total cost of linac center-line components: $C_L = 0.025\,L$

Cost of linac injector: $C_I = 0.4$

Cost of linac beam transport system: $C_{TR} = 0.3$

Total cost of linac tunnel and klystron gallery: $C_{LB} = 0.011\ L$

Total cost of storage ring components: $C_{ST} = 0.020 \times 2\pi pR$

Total cost of storage ring buildings: $C_{STB} = 0.005 \times 2\pi pR$

Total cost of system: $C_T = 1.1\Sigma$ all above costs.

The rationale behind these expressions is as follows. It is assumed that the cost of a klystron-modulator system with a SLAC duty cycle of 10^{-3}, fully driven with rf power, is \$0.1 million, and that at any other duty cycle the cost scales linearly with D_{RF}. Beam center-line components fully supported and equipped with vacuum system and alignment are assumed to cost \$0.025 million per meter. The linac building costs are estimated at \$0.005 million per meter for the tunnel and \$0.006 million per meter for the klystron gallery, or \$0.011 million per meter, total. Storage ring magnets with their supports, including dipoles, quadrupoles, sextupoles, septa and kickers with their corresponding power supplies are estimated at \$0.02 million per meter and the corresponding buildings at \$0.005 million per meter. The final 1.1 coefficient in front of the summation sign takes into account common experience that whatever the total cost of the system happens to be, 10% must be added for all instrumentation. Finally, it is interesting to see what the power costs for such an installation would be over a period of 10 years. The expression given below,

$$C_{10Y} = 5000 \times 10 \times 0.06\ (P_{AC_{KW}} + 2000) \times 10^{-6}$$

$$= 3(P_{AC} + 2) \qquad \text{with the linac } P_{AC} \text{ in MW}$$

assumes 5000 hours of operation per year over 10 years, a hypothetical future cost of 6¢ per kW-hour and 2 MW of extra power for the ring.

These various costs have been plotted in Figs. 10-16 , again as a function of R. We see from Fig. 15 that there is a broad minimum around R = 30 meters, quite independently of which type of accelerator section is used, with a slight advantage showing up for curve 1, i.e., the SLAC-type sections. Based on these results, a typical list of parameters for a machine design is shown in Table I and costs are shown in Table II.

Table I

POSSIBLE MACHINE PARAMETERS

Maximum energy	$E = 2$ GeV
Maximum cw current	$i_{cw} = 10^{-4}$ A
Allowable energy decay	$k_1 E = 40$ MeV
Stretcher magnetic radius	$R = 30$ m
Stretcher circumference	340 m
Stretcher magnetic induction	$B = 0.22$ T
Linac frequency	$f = 2856$ MHz
Linac duty cycle	$D_{RF} = 2.03 \times 10^{-3}$
Linac repetition rate	$n_{pps} = 1043$ pps
Linac filling time	$t_f = 0.82$ µsec
Linac RF pulse length	$t_{RF} = 1.95$ µsec
Linac beam pulse length	$t_B = 1.13$ µsec
Linac section length	$\ell = 3$ m
Linac section attenuation	$\tau = 0.57$
Linac total length	$L = 126$ m
Linac peak current	$i_{pk} = 101$ mA
Number of linac klystrons and sections	$N = 33$
Steady-state beam loading	$\Delta E_B = 141.5$ MeV
Efficiency	$\eta = 8.2\%$
Linac AC power	$P_{AC} = 4.85$ MW

Table II

SYSTEM COSTS

		$\$ \times 10^6$
Linac power components		7.14
Linac section components		3.15
Linac injector and transport		0.70
Linac buildings		1.40
Storage ring components		6.80
Storage ring buildings		1.70
Total Construction Cost	1.1 x $20.89 =	$23
Engineering & Design Cost		5
Total Cost		$28 million
Ten-Year Power Costs		$20 million

Technical Problems and Conclusions

What would be some of the problems with a basic design such as the one shown in Table I? Consider the linac and the ring successively:

Linac

The linac design would be very straightforward. The RF duty cycle being twice that of SLAC, it would require SLAC-type klystrons, possibly with improved collectors, and modulators with larger magnetic components such as power transformers, chokes and pulse transformers. Cooling of the RF sections would have to be doubled. With 1.95 μsec long RF pulses and 1.13 μsec beam pulses, there would be no particular difficulties. The beam current of ∿ 100 mA would be easy to obtain. The beam loading of 141.5 MeV or 7% would be entirely transient since the beam pulse length would barely exceed the section filling time (0.82 μsec) but it should not be too difficult to reduce by pulse staggering and other techniques. If one wanted to deliberately spread the spectrum of each individual bunch to, say 40 MeV, for optimum extraction (see below), this could be done by running somewhat wider bunches than is normally done, on one side of the rf wave crest. For example, an 11.4° wide bunch placed on one side of the crest produces an inherent spectrum of 2%. Both the injector and the beam transport system with the momentum analyzing slit would be very conventional.

Ring

The ring design would not pose any major problems except for the injection and the extraction. The bending field of 0.22 T would be trivial. The vacuum system would not have to be extravagant because there would be no long storage times. There would be no RF system and therefore no complications arising from it. Injection would probably be done in the vertical plane. The kicker rise time and fall time would be as short as possible, say ≤ 0.1 μsec, with a flat-top of 1.13 μsec. One would synchronize the linac injector with the kicker in such a way that the front of the injected beam upon coming around after its first turn, would just miss the fall time of the pulse. Thus, after this injection pulse, there would be a small fraction of the circumference of the ring (∿ 30 m) that would not be filled. However, after a few turns, this gap would become filled because of the absence of the RF system. In addition, because of the inherent energy spread of the beam, the linac RF structure would become smeared out.

The main technical problems that must be solved in the ring are:

a) Uniform continuous beam extraction.

b) Operation of the system at any energy other than the maximum.

These two problems are intimately interrelated. In synchrotrons, the most common method of extraction is to induce a one-third integral betatron resonance. A time-varying field quadrupole is ramped up gradually. Electrons in the core of the beam's phase space are stable and remain stored. Electrons on the periphery undergo growing betatron oscillations until they get outside the triangle formed by the three separatrices and are caused to "jump" across a septum, generally made out of thin wires. The jump is discontinuous and extraction can take place without appreciable beam loss on the septum. If this method were to be used, one would have to study carefully the phase space and energy spectrum of the extracted beam to see that they could be kept within acceptable limits. Operation at any energy below 2 GeV would be very similar. The linac would be tuned up to the desired operating energy. Beam loading might be reduced in the idle sections, for example through detuning by operating them at a drastically lower temperature. The linac beam current would be kept at the same level as at 2 GeV and the energy spectrum would have to be controlled to within the acceptance of the ring. The energy loss through synchrotron radiation would decrease very rapidly (as E^4), which would be an advantage for the extracted beam. The linac repetition rate would remain fixed at all energies and the extracted beam current would accordingly be energy-independent.

Another method of extraction, schematically illustrated in Fig. 1, makes use of the inherent energy spread in the beam. The beam is spatially dispersed in one of the straight-sections and the low energy slice is gradually peeled off by the septum from where it is extracted. The advantage of this method is that it gives a narrow output energy spectrum. The disadvantage is that since the energy spread of the stored beam is a continuum, there is no discontinuous "jump" across the septum wires and some of the beam is lost on the wires and/or scattered back into the stored portion of the beam. For example, if the beam is dispersed to a transverse dimension of 400 mm and the thickness of the wires is 0.05 mm, the beam will move inward by $\sim 400/1000 = 0.4$ mm per turn, causing $\sim$ 12.5% interception. With a stored beam energy spectrum of 40 MeV (2%), the extracted beam could have a spectrum with a lower limit of $\sim$ 40 MeV/1000 = 40 keV. At any energy below 2 GeV, the natural energy decay would be slower (going again as E^4). Within a certain range, it would be possible to force the energy decay (2%) to take place within the same time by using a tunable wiggler magnet system. The linac peak current, repetition rate and extracted current could all then remain the same as at 2 GeV. Alternatively, it would be possible to store the beam over longer periods, thereby reducing the linac and injection repetition rate, and taking a loss in extracted current accordingly.

A combination of the two above methods or variations thereof might also be feasible. With a well-tuned extraction system and the linac RF structure erased from the beam, the output current of the stretcher would be truly continuous in time, except for the $\sim$ 1043 interruptions due to the injection kicker pulse, a total off-time of $\sim$ 1.25 msec leading to a duty cycle of close to 99%.

Acknowledgment

The author wishes to thank Helmut Wiedemann of SLAC for his help in the stretcher ring design and Barbara Woo for her computation work.

References

1. G. A. Loew, "Electron Linacs," Proceedings of the 1976 Proton Linear Accelerator Conference, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada (September 1976) pps. 217-229, or Stanford Linear Accelerator Center Report No. SLAC-PUB-1830, (1976).

2. R. B. Neal, Editor; G. A. Loew, Co-Editor, "The Stanford Two-Mile Accelerator," W. A. Benjamin, Inc., (1968).

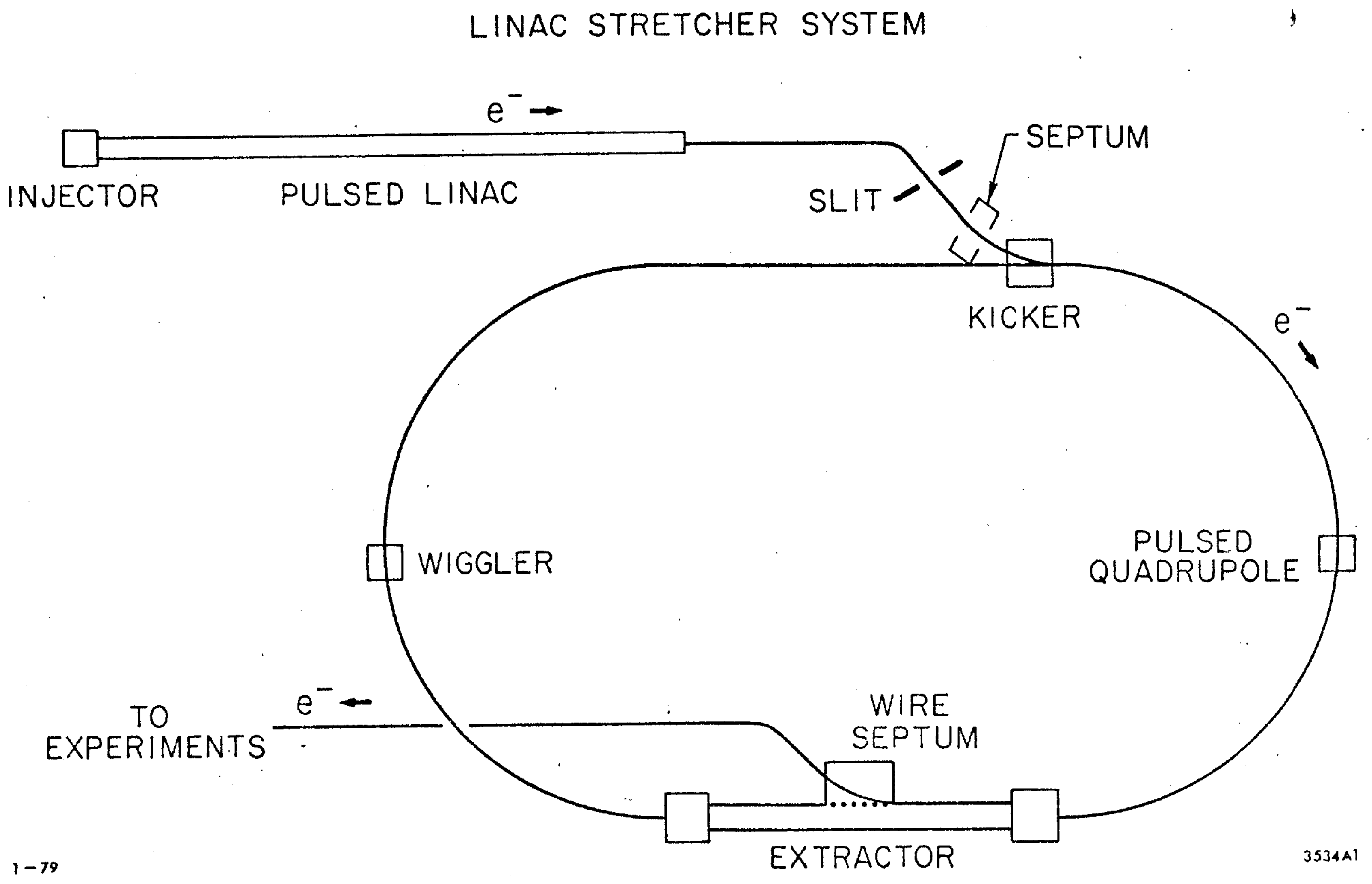
LINAC STRETCHER SYSTEM
e⁻
INJECTOR
PULSED LINAC
SLIT
SEPTUM
KICKER
e⁻
WIGGLER
PULSED
QUADRUPOLE
TO
EXPERIMENTS
e⁻
WIRE
SEPTUM
EXTRACTOR
1-79
3534A1

FIGURE 1

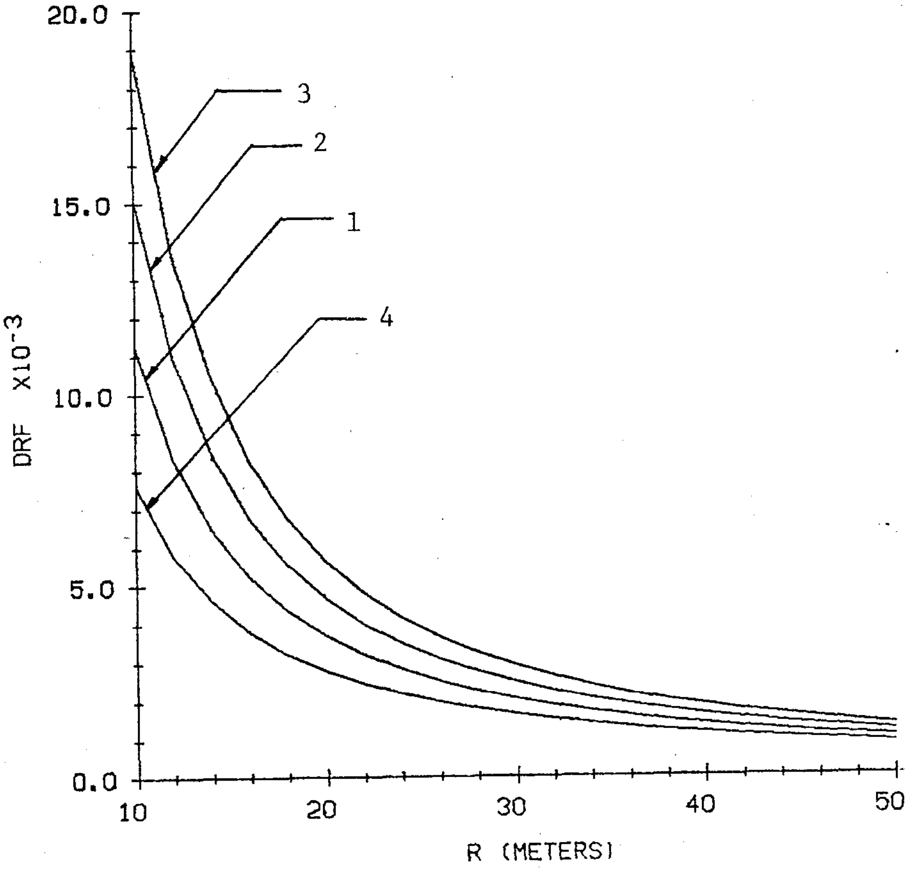

FIG. 2. LINAC RF DUTY CYCLE VS STRETCHER MAGNETIC RADIUS

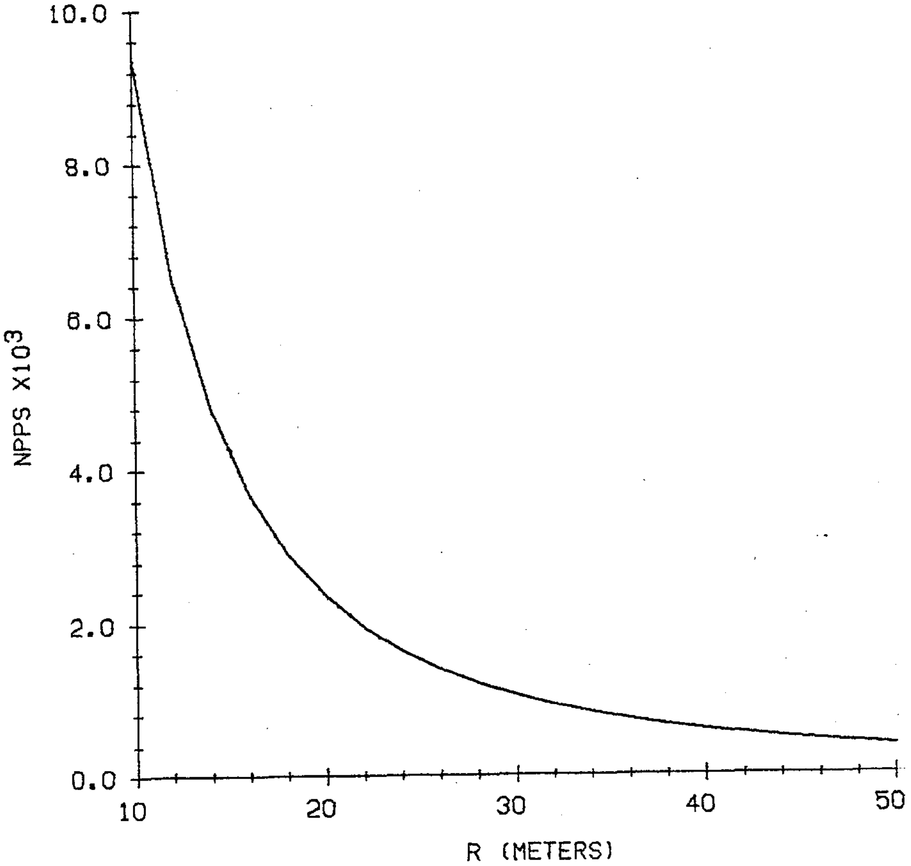

FIG. 3. LINAC REPETITION RATE VS STRETCHER MAGNETIC RADIUS

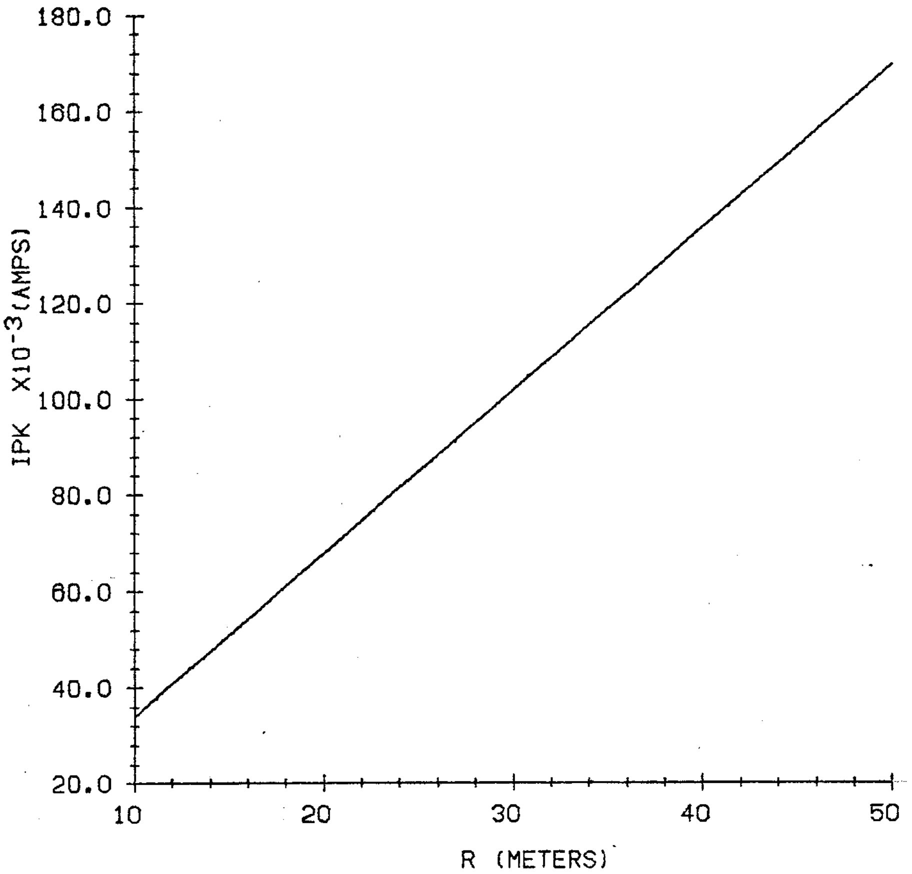

FIG. 4. LINAC PEAK CURRENT VS STRETCHER MAGNETIC RADIUS

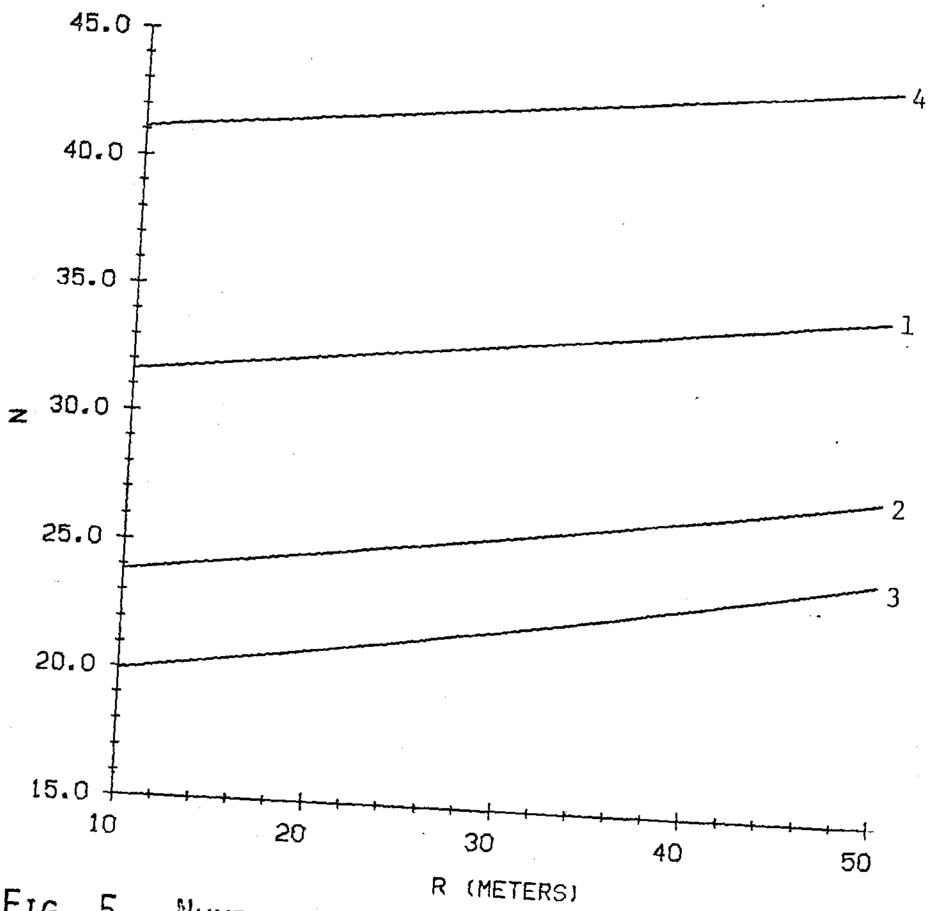

FIG. 5. NUMBER OF ACTIVE KLYSTRONS AND LINAC SECTIONS VS STRETCHER MAGNETIC RADIUS

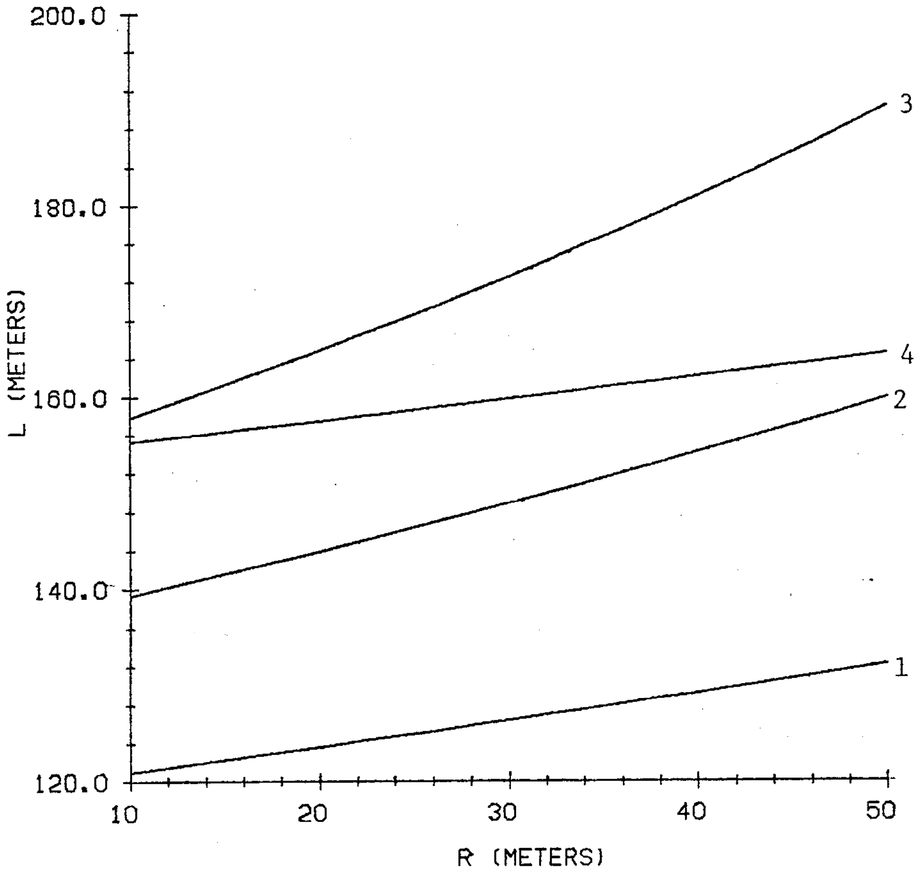

FIG. 6. LINAC TOTAL LENGTH VS STRETCHER MAGNETIC RADIUS

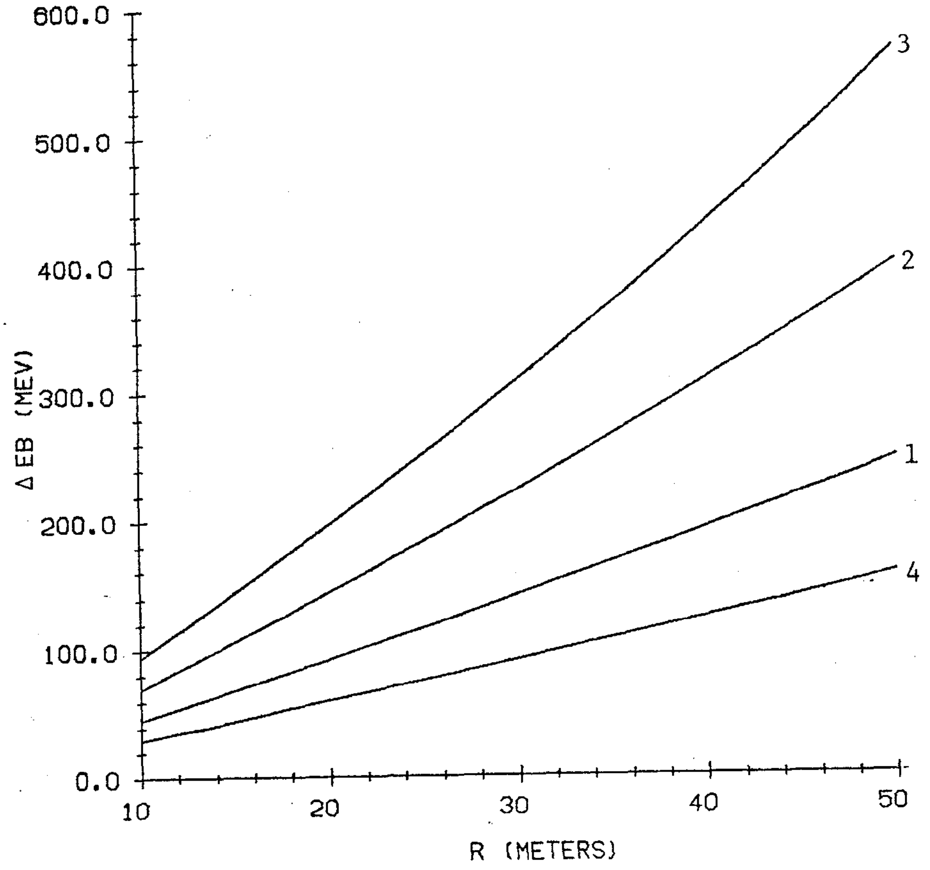

FIG. 7. LINAC STEADY-STATE BEAM LOADING ENERGY LOSS VS STRETCHER MAGNETIC RADIUS

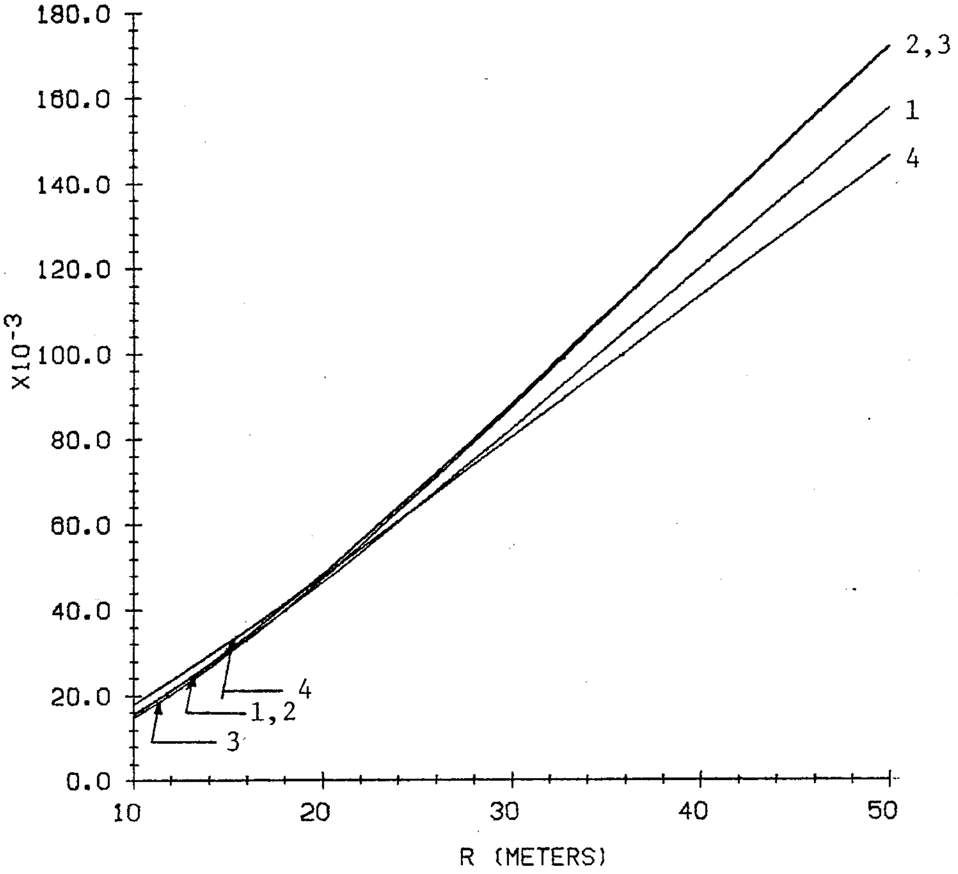

FIG. 8. CONVERSION EFFICIENCY FROM RF TO BEAM POWER VS STRETCHER MAGNETIC RADIUS

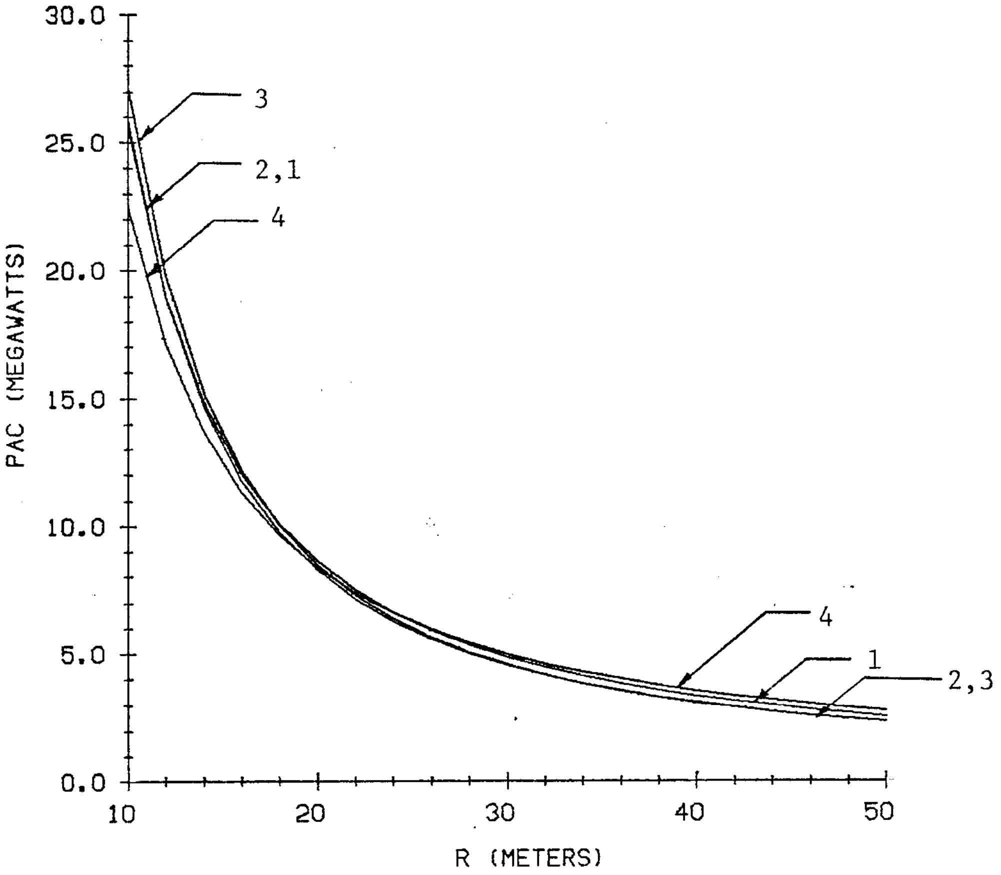

FIG. 9. LINAC AC POWER VS STRETCHER MAGNETIC RADIUS

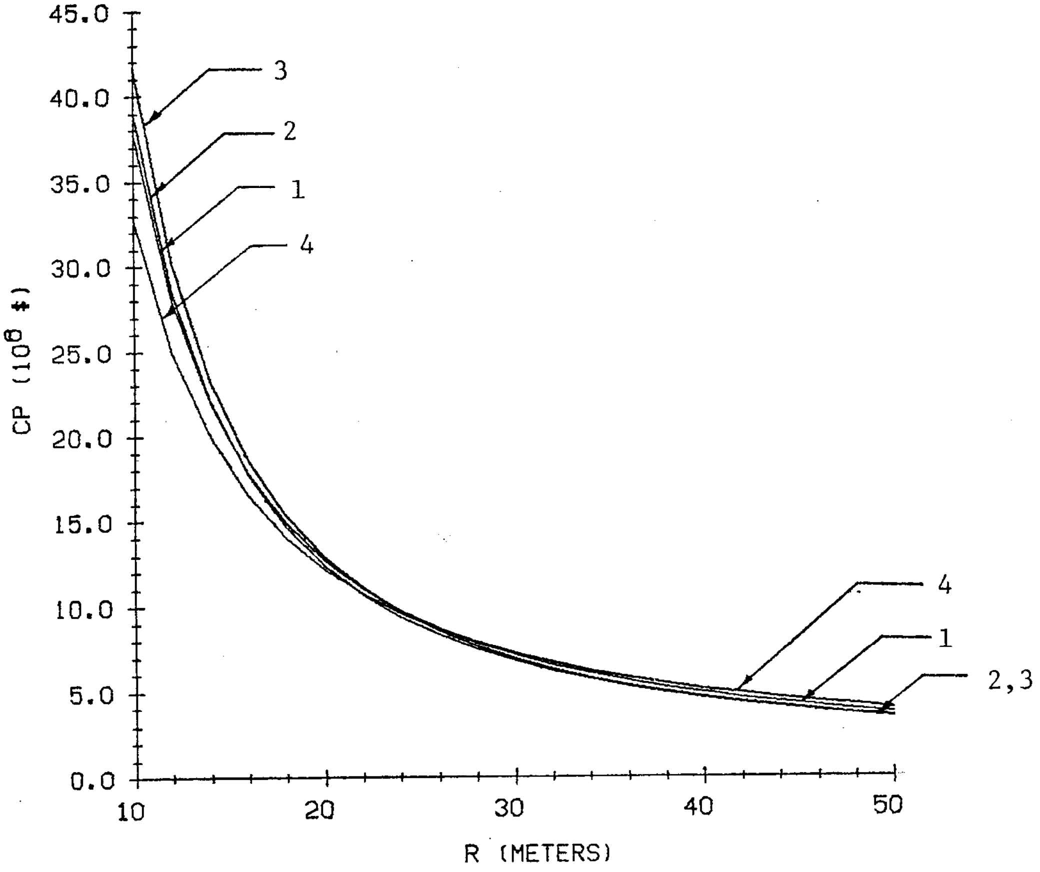

FIG. 10. COST OF LINAC POWER COMPONENTS VS STRETCHER MAGNETIC RADIUS

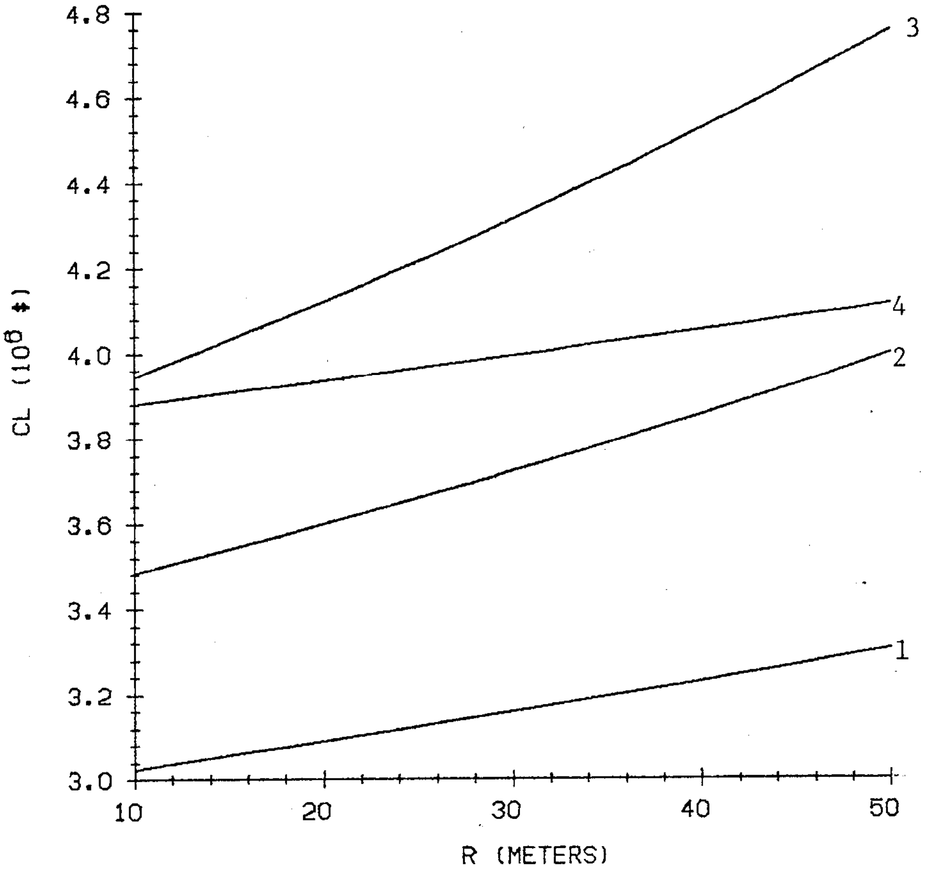

FIG 11. COST OF LINAC STRUCTURE COMPONENTS VS STRETCHER MAGNETIC RADIUS

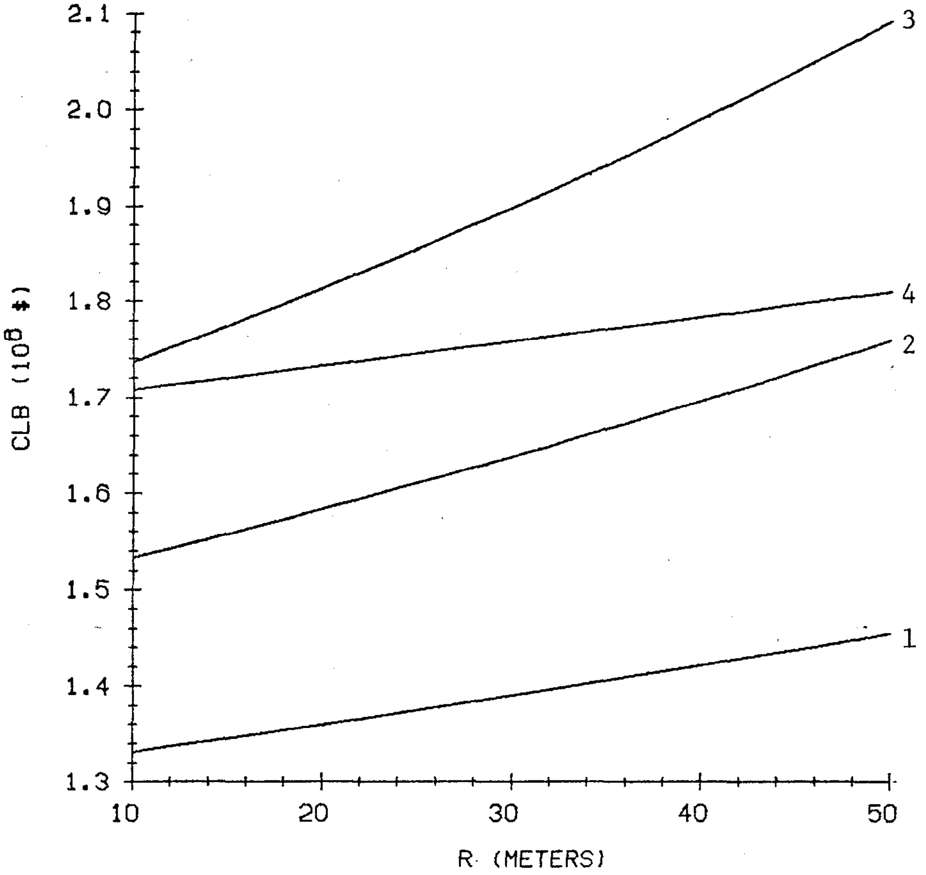

FIG. 12. COST OF LINAC BUILDINGS VS STRETCHER MAGNETIC RADIUS

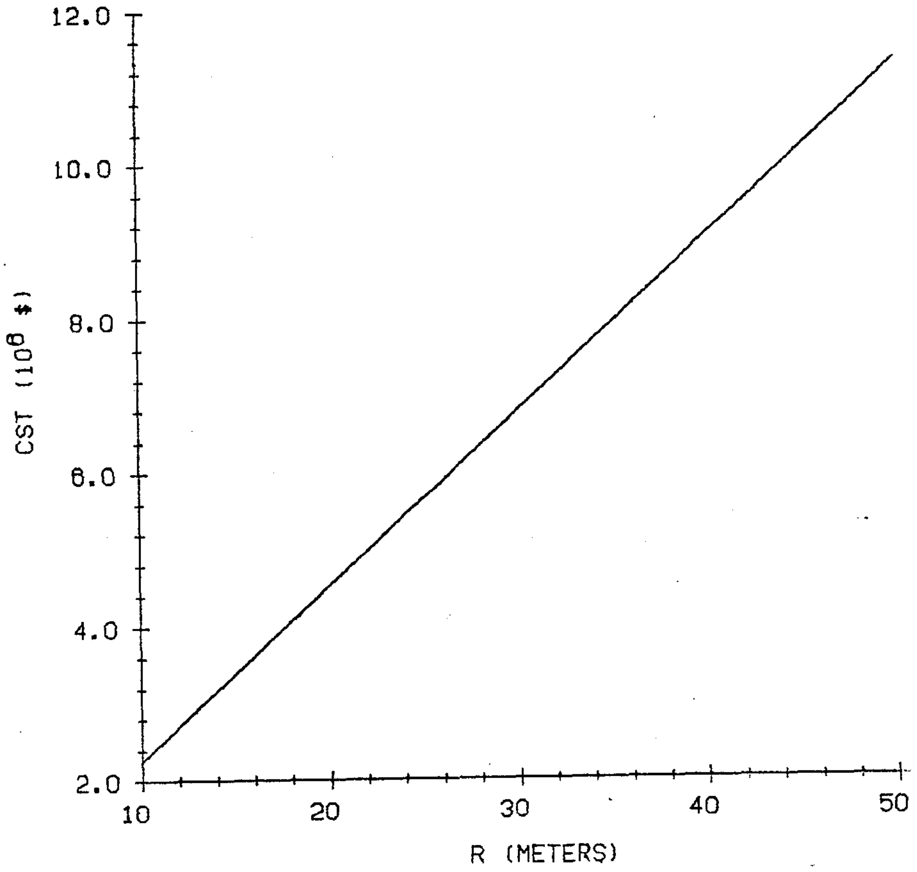

FIG. 13. COST OF STRETCHER COMPONENTS VS MAGNETIC RADIUS

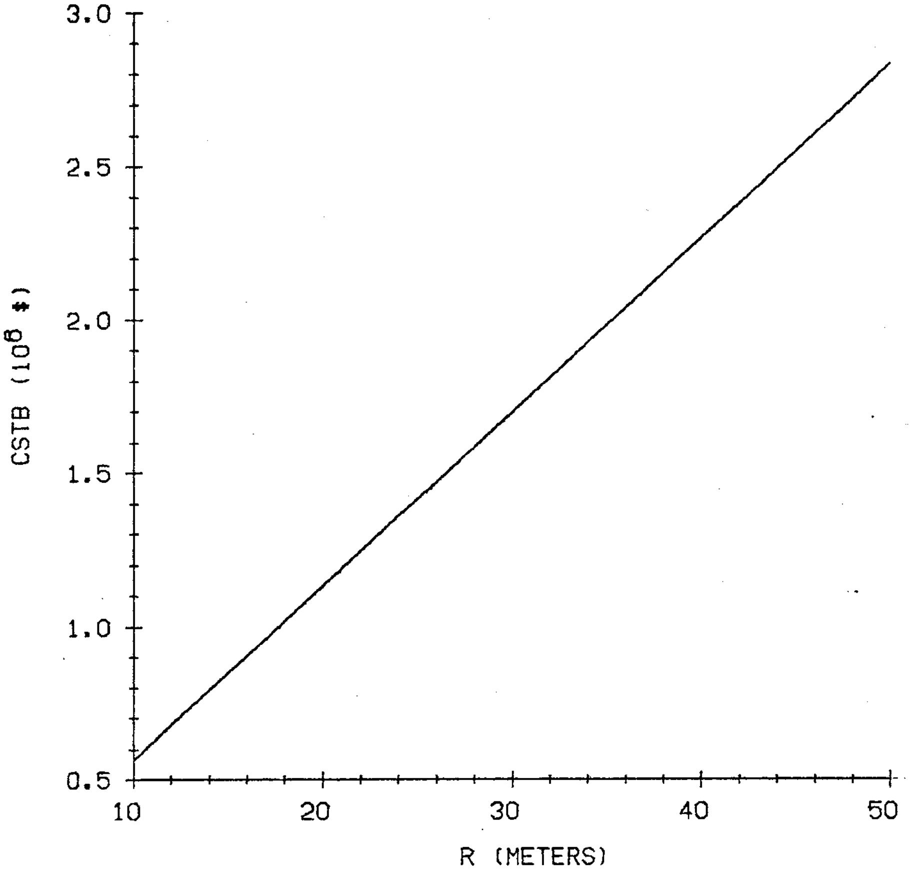

FIG. 14. COST OF STRETCHER BUILDINGS VS MAGNETIC RADIUS

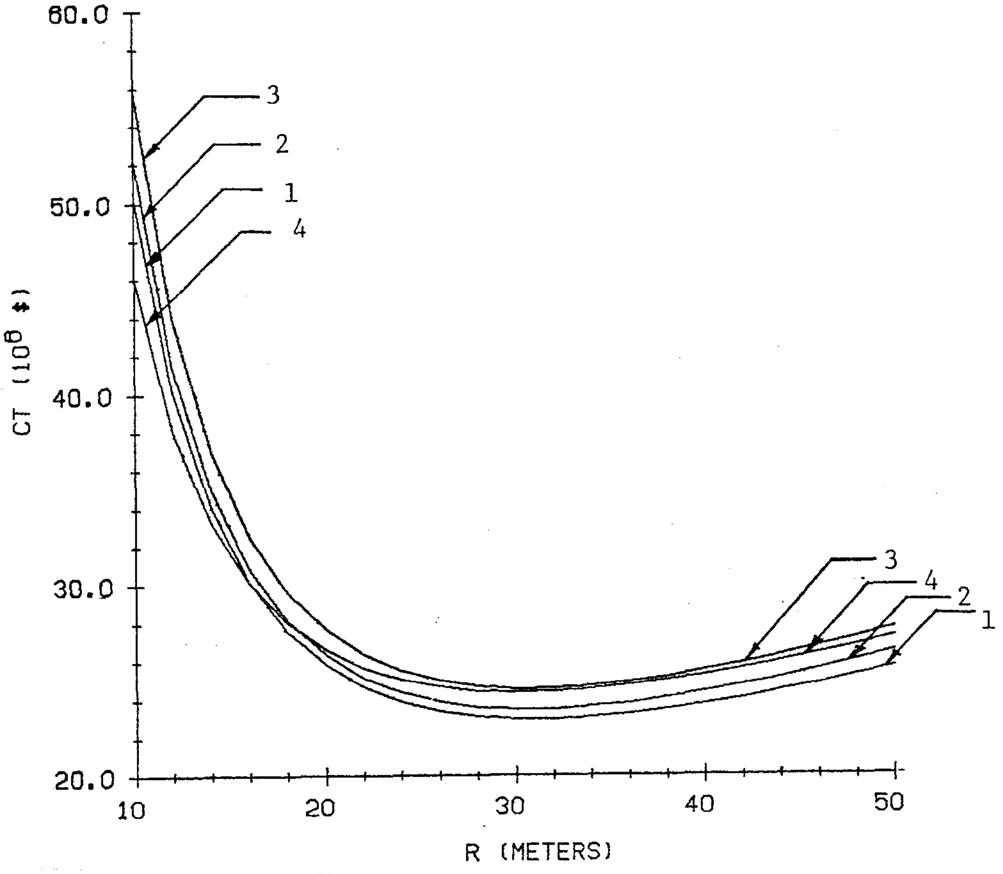

FIG. 15. TOTAL SYSTEM COST VS STRETCHER MAGNETIC RADIUS

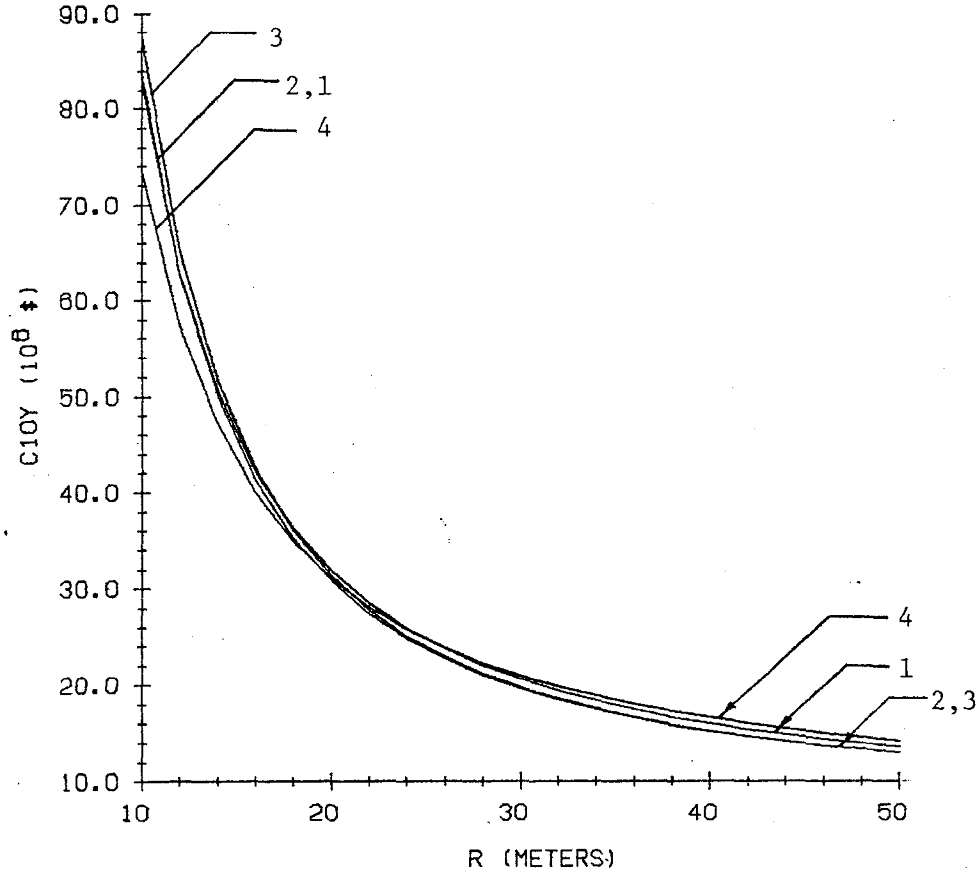

FIG. 16. TEN-YEAR POWER COST VS STRETCHER MAGNETIC RADIUS