SLAC-PUB-1132
(ACC)
October 1972

THE STANFORD RECIRCULATING LINEAR ACCELERATOR*

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1. History

When the Stanford two-mile accelerator was originally proposed in 1956 an economic analysis was made to balance the investment and 10-year operating costs relating to physical length, on the one hand, and radiofrequency, on the other. As a result it was decided to run the machine at a gradient of 20 GeV in two miles, or 2 MeV per foot, which is below the gradient the RF structure could tolerate by at least a factor of two. The original plans envisaged that, should physics interest so indicate, and should the cost of radiofrequency power decrease, an increased number of power sources by as much as a factor of four could be introduced. Encouraged by the productivity of SLAC for physics, including not only the fields of electron-photon physics but also as a secondary particle factory, it was decided several years ago to develop plans for advancing the energy of the installation. However the cost of proceeding along the originally planned direction, that is replicating the klystron and modulator stations, appeared excessive; quadrupling the RF power leading to a doubling of energy might cost as much as $80 million, while intermediate steps would have corresponding price tags.

SLAC also undertook an extensive study looking at a complete conversion of the accelerator to a microwave superconducting configuration. This study, published in 1970, considered such a conversion feasible in general, but the question of maximum gradient and thus beam energy attainable by this method was then and still is open. The price of such a conversion would be in the $100 million range and from the physics point of view this cost would only be remotely justifiable if gradients as high as 10 MeV per foot could be practically attained in a predictably reliable manner. At the current state of the art this figure is still far from reality.

Starting from these historical facts SLAC established a group to review various proposals to increase energy by various schemes of recirculating the beam. Time does not permit me here to describe the alternatives considered; the scheme particularly advocated by William B. Herrmannsfeldt constitutes the basis of the present RLA design. The basic principle is the following: After injection and acceleration of the beam in the usual way the beam is ejected into a storage loop which holds the beam for the interpulse interval. The electrons circulating in the storage loop can either be slowly extracted into the beam switchyard for physics use, thus yielding a good duty cycle electron beam near the current operating energy of SLAC, or, alternately, the beam can be reinjected after storage into the accelerator, thereby receiving a final energy of roughly twice the initial amount. Thus this installation can serve the dual purpose of increasing the duty cycle of SLAC roughly one hundredfold (to about 7%) near current energy and roughly doubling its energy at the current duty cycle, but as it turns out, at somewhat decreased intensity.

2. General Description

The principle of the recirculating linear accelerator is illustrated in Figure 1. Beam storage occurs for 120 revolutions in a loop of total length of 6.9 kilometers. A large part of the storage occurs in straight sections of the loop while only a smaller part occurs in magnets of total bend angle 480^o ($360^o + 60^o + 60^o$ reverse bends). The radiation losses incurred during these bends are compensated for in an RF structure consisting of three, or possibly two sectors (each 100 meters in length) of the current accelerator. The period of recirculation is 23 μsecs and, since the beam pulse is 1.6 μsec long, the duty cycle during storage and therefore also for the slow extracted beam is 7%.

The expected performance of RLA depends on a number of factors not as yet fully determined. Among these are:

1) The growth of klystron power along the two-mile machine

2) Choice of synchrotron radiation compensating RF structure.

Currently the SLAC accelerator is fed by a mixture of klystrons operating at peak powers of 20 MW and 30 MW, respectively; a gradual replacement program will lead to a full 30 MW complement; when completed this program will lead to a 25 GeV energy gain in the two-mile structure. A developmental tube has reached 40 MW peak output; its efficiency near 50% has made it possible to reach this figure using the present modulator at the present repetition rate of 360 pps. Modification of the pulse transformer should make it possible to reach an output of 60 MW at the cost of reducing the repetition rate to 180 pps; at this value the energy gain of the structure would become 35 GeV. Note that for the RLA this number controls the energy gain for the second passage through the accelerating structure; the energy permissible for storage is set by the parameters of the loop (magnet parameters and RF structure and power in the loop).

Current plans call for using regular SLAC accelerating structures as synchrotron radiation "make-up" units. Under these circumstances a circulation energy ranging from 17.5 GeV (loaded) to near 20 GeV appears attainable. If in the future a superconducting microwave structure can be developed, a loaded storage energy of 25 GeV should be feasible.

Table I gives the table of operating parameters unde under the range of assumptions cited.

Figure 2 indicates the projected growth of energy with time as the various improvements now projected materialize.

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

(Presented at the Conference on Proton Linear Accelerators, Los Alamos, New Mexico, October 10-13, 1972.)

TABLE I

SUMMARY TABLE OF OPERATING PARAMETERS

	High Energy Mode		High Duty Cycle Mode		Accelerator Only Mode	
Lightly Loaded Condition						
Output Beam Energy (GeV)	45.3	61.4	19.5	25	25.8	36.4
Recirculating Beam Energy (GeV)	19.5	25	19.5	25	-	-
Heavily Loaded Condition						
Output Beam Energy (GeV)	41.5	58.7	17.5	24.1	22.9	33.5
Recirculating Beam Energy (GeV)	17.5	24.1	17.5	24.1	-	-
Peak Output Beam Current (mA)	30	30	0.25	0.25	82	82
Number of Electrons Per Pulse ($\times 10^{10}$)	30	30	0.25	0.25	82	82
Average Beam Current (μA)	17.2	8.6	17.2	17.2	47	23.5
Average Beam Power (kW)	710	500	300	415	1075	790
Both Conditions						
Beam Pulse Repetition Rate (pps)	360	180	4×10^4	4×10^4	360	180
Beam Pulse Length (μsec)	1.6	1.6	1.6	1.6	1.6	1.6
Duty Cycle (%)	0.06	0.03	7	7	0.06	0.03
Output RF Peak Power Per Klystron (MW)	30	60	30	30	30	60
RF Pulse Repetition Rate (pps)	360	180	360	360	360	180

Note: The left-hand column under each heading gives the beam parameters achievable with the initial complement of equipment for the Recirculating Linear Accelerator (RLA). The right-hand column under "High Energy Mode" gives beam parameters achievable after later expansion to 60 MW klystrons and 25 GeV storage energy capability. The right-hand column under "High Duty Cycle Mode" requires 25 GeV storage energy capability but 30 MW klystrons are sufficient in this case. The right-hand column under "Accelerator Only Mode" requires 60 MW klystrons.

3. Orbit Dynamics

The storage loop has to meet a number of requirements: (1) orbits must be essentially isochronous so that on reinsertion into the accelerator the phase spread shall not unduly broaden the energy spectrum of the emerging beam; (2) the phase space emerging from the recirculator must not exceed the phase admittance of the accelerator*; (3) mechanical tolerances and magnet design parameters must be reasonable; (4) economic factors such as magnet design costs and RF power required to compensate for synchrotron radiation must be considered.

Isochronicity is obtained by the use of the back bends shown in Figure 1; these bends thus meet the dual purpose of making isochronicity possible and locating a large fraction of the loop inside the original accelerator tunnel, thus obviating the need for constructing a separate housing for most of the length of the machine. The bending rings have an average radius of 95 meters. This value is primarily determined by the available real estate; space constraints necessitate design of the magnet lattice with maximum compaction. Accordingly a separated function design was rejected in favor of an AG system.

*Presently $0.3\pi \times 10^{-6}$ meter radius in each plane at 17.5 GeV; this value could be doubled by adding further closer-spaced lenses or pulsing lenses at the present location during the second passage (thereby restricting the repetition rate to 180 pps).

The details of the lattice are mainly controlled by the requirement to minimize the transverse and longitudinal phase space growth due to quantum fluctuations induced by synchrotron radiation. The unit cells of the magnet lattice produce a 5° bend and each cell consists of one focusing and one defocusing magnet. As it happens the conditions to minimize radial phase space growth require that the defocusing magnet produce most of the bend while the focusing magnet is almost a pure quadrupole, that is the central beam passes quite near a zero field point. The exact choice of the lattice parameter is not as yet frozen, but Table II shows the range of presently contemplated numbers.

TABLE II

LATTICE CHARACTERISTICS AT 20 GeV MAGNET PARAMETERS

Case	Magnet	Bend (deg)	B_0 (kG)	dB/dx (kG/cm)
1	Focus	.7	4.08	1.78
	Defocus	4.3	8.82	-.48
2	Focus	0.4	2.33	1.78
	Defocus	4.6	9.43	-.48
3	Focus	0	quadrupole	1.78
	Defocus	5.0	10.24	-.48

The three cases in each table refer to the same parameters, respectively.

An increasing value of B_0 in the main bending (defocusing) magnets increases the radial damping but also increases the spread of the synchrotron phase oscillations. Therefore the actual design chosen becomes a compromise between transmission through the accelerator structure after reinsertion and the tolerable energy spectrum of the final beam. A design between Case 2 and Case 3 appears to be reasonable; it is expected to yield better than 90% transmission after reinsertion (at presently measured admittance) and give a bunch length (twice standard deviation) of $\pm 8^o$ in phase giving a 1% spread in energy gain during the second pass, or 0.5% total energy spread. Since the quantum fluctuations do not drive the vertical phase space, additional optimization can be achieved if vertical and horizontal motions are mixed in such a way as to divide the emittance between the two planes. Whether this measure will have to be taken is not as yet determined.

Isochronicity is achieved by attaining a shorter path for higher momentum rays in the two 30^o "reverse bend" magnet systems; to first order perfect compensation is possible, but second order effects limit the "dilation factor," i.e., the ratio of fractional path length shift to fractional momentum shift, to values between 10^{-5} and 10^{-4}.

Considerable thought has been given to the subject of instabilities. Resonances up to the third harmonic of the fundamental tunes can be avoided by appropriate settings of correcting quadrupoles. Higher order resonances are unlikely to produce significant effects during the 2.8 msec storage time.

The beam-breakup (BBU) currently limiting SLAC performance is not expected to occur at currents lower than those limited by the power of the RF system. Should this estimate prove incorrect, the BBU threshold can be raised by stronger focusing in the RF sections or by feedback methods. A longitudinal regenerative buildup analogous to BBU has been conjectured by M. Sands, based on successive coupling of the circulating beam to the RF traveling wave section, assumed to be imperfectly tuned. Calculations estimating this effect are not complete but the instability threshold appears to be comfortably high.

Other instabilities considered are resistive wall effects, radial interactions with other structures, the effect of RF noise, residual gas effects, etc. None of these appear serious but definitive calculations remain to be done.

4. RF Systems

The requirements of the radiofrequency system increase steeply as a function of the required energy of the recirculator and so does the problem engendered by quantum fluctuations. Design requirements are that 20 GeV can be circulated at small current and that the fully loaded machine can sustain a recirculating loop energy of 17.5 GeV. Figure 3 shows the loading characteristics of the RF system chosen under a variety of assumptions. The power sources to feed the accelerator sections are especially designed klystrons operating at the circulation frequency (43.5 kHz). Such tubes and their modulators have been designed and tested at SLAC at powers of 220 kW peak and 20 kW average. Current plans are to feed three sectors, each 100 meters in length, with eight of these tubes each. Considerable cost saving can be produced if instead 500 kW peak tubes operating at this repetition rate can be developed feeding only two sectors and in addition the loading characteristic of the configuration with a smaller number of sectors is less steep as indicated in Figure 3. Therefore the stored current at the design energy of 17.5 GeV will be larger.

5. Magnets and Vacuum System

Altogether 330 individual magnets will have to be fabricated. The specifications for the main lattice magnets imply rather high gradients and stiff tolerances. Laminated construction will be used and model work is proceeding; thus far design has been based on computer calculations.

The vacuum system is designed for an average pressure of 5×10^{-7} Torr. Following SPEAR experience extruded aluminum sections will be used in the curved sections; however the synchrotron radiation bombardment (1 kW/meter maximum) is less than for SPEAR and the X-ray spectrum is much harder, decreasing the radiation induced gas desorption problem. Straight sections will be stainless steel and pumping by localized small ion pumps appears adequate.

6. Slow Extraction

The slow spill arrangement to extract a high duty cycle beam from the storage loop involves many features similar to the methods considered at large proton installations. Two alternative solutions are still under consideration: one is a "scattering out" method using a thin Coulomb scatterer, and the other is slow ejection through a pair of highly nonlinear magnetic perturbing elements introduced as an insertion of unit transfer matrix. Figure 4 shows how these perturbations are produced by a bifilar loop placed away from the nominal beam diameter. The electron beam is moved in a programmed manner toward the perturbation. Part of the beam is deflected (vertically) past an electrostatic septum into an ejection channel; the balance is reinserted into the loop via the exactly cancelling perturbation. Both methods have been extensively computer-simulated, indicating that an extraction efficiency in excess of 95% appears reasonable.

7. Physics Objectives

Let me now turn briefly to the discussion of physics usefulness of RLA. A principal purpose of the expanded accelerator is of course to extend the range of attainable parameters in the deep inelastic electron scattering experiments which have given rise to so much theoretical interest by indicating the existence of further substructure of the proton. Figure 5a and 5b show plots of the two customary kinematic variables (the square of the four momentum transfer and the energy of the final state hadron system) which are currently accessible to SLAC and later accessible to RLA. Expected counting rates for the present and future operation are shown for "single arm" experiments in which the scattered electron is observed by conventional spectrometers. In addition to such single arm experiments a great deal of interest has recently been focused on more detailed studies of the reaction products from inelastic scattering experiments. Although impressive progress on this subject has been made both at SLAC and also at Cornell and DESY, the present SLAC duty cycle limits what can be accomplished. Therefore this field of inquiry would be greatly strengthened by the slow extraction mode of RLA operation.

Both two-body and multibody photoproduction experiments can be extended by RLA into regions currently inaccessible at good intensities. Although energy dependence of cross sections is not expected to yield many surprises, the extension of measurements to larger momentum transfers should be most instructive, in particular for vector meson photoproduction. The use of the polarized photon beams will be particularly useful.

Secondary beams at RLA should be greatly superior and more flexible than those at the present accelerator. Intensities of positive kaons and antiproton beams are currently noncompetitive at SLAC with those attainable at proton accelerators; this deficiency will be removed. The neutral kaon beams at SLAC have already been extremely useful tools due to their much lower neutron contamination relative to proton accelerators; in addition the RF structure of the beam is a highly valuable timing tool. There is little question that the combination of this feature with the good duty cycle of RLA should make neutral kaon beams at SLAC superior to those in any other facility. In addition the power of the secondary beams now available at SLAC, including those of the laser back-scattered gamma ray beams and polarized gamma ray beams produced by either radiation in single crystals or by selective filtration of gamma rays in crystalling graphite should be greatly enhanced.

RLA also might well become an important tool in weak interaction physics. Intensity available at good duty cycle might be adequate to study the inverse β decay reactions at high momentum transfer and new searches for the intermediate boson can be undertaken with a predictable cross section. In addition RLA is expected to enhance greatly the power of SLAC in the field of more conventional strong interaction physics using either large wire chamber spectrometers or bubble chambers. For the former category the good duty cycle feature removes the one disadvantage SLAC had relative to such work with proton machines and for the latter technique the high repetition rate of SLAC makes possible the further adaptation of hybrid bubble chamber techniques in which the flashing of the lights and triggering of the cameras is activated by a particle detection system which pre-tags the event of interest. The recently developed superconductive shield tube will be particularly powerful in connection with multibody spectrometers.

8. Conclusion

This has been only a brief outline of the historical motivation and the design of RLA. The installation should further greatly increase SLAC's power as a research tool in Physics; RLA is expected to double the energy of SLAC and increase its duty cycle 100-fold at present energy; since the projected cost is about 10% of the initial capital investment in SLAC, this improvement program appears to be of very great value in relation to its cost.

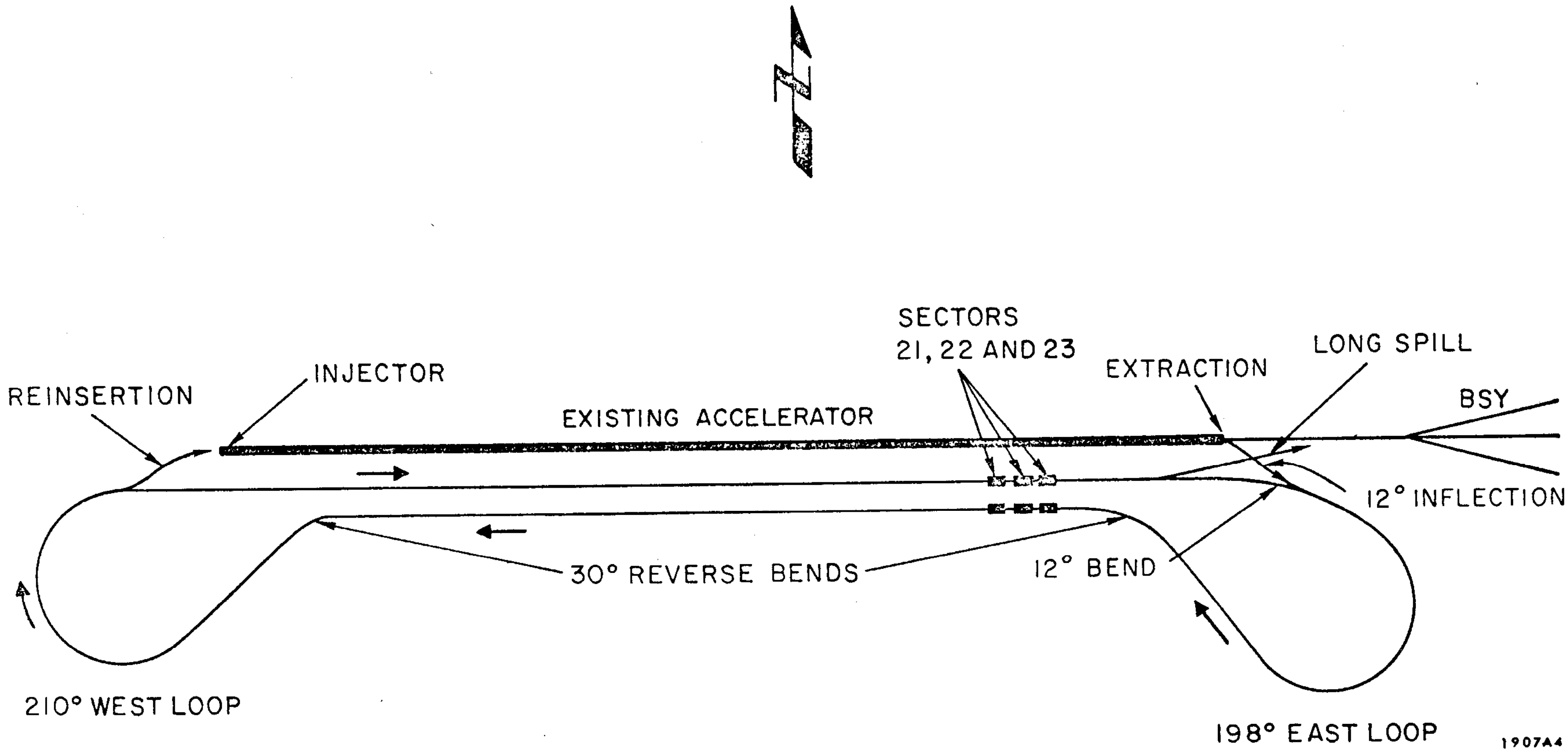


Figure 1. Schematic layout of the recirculating linear accelerator.

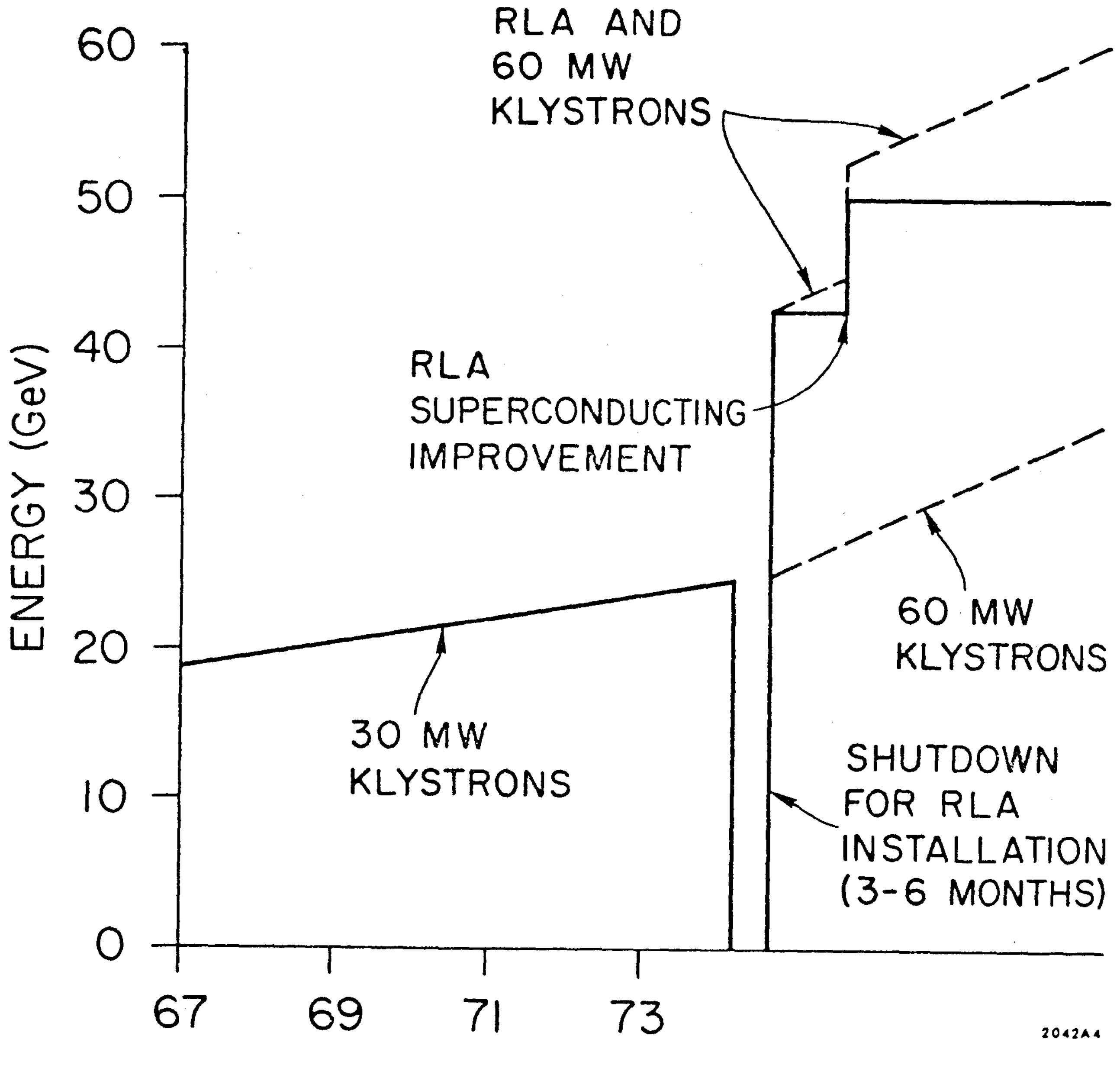
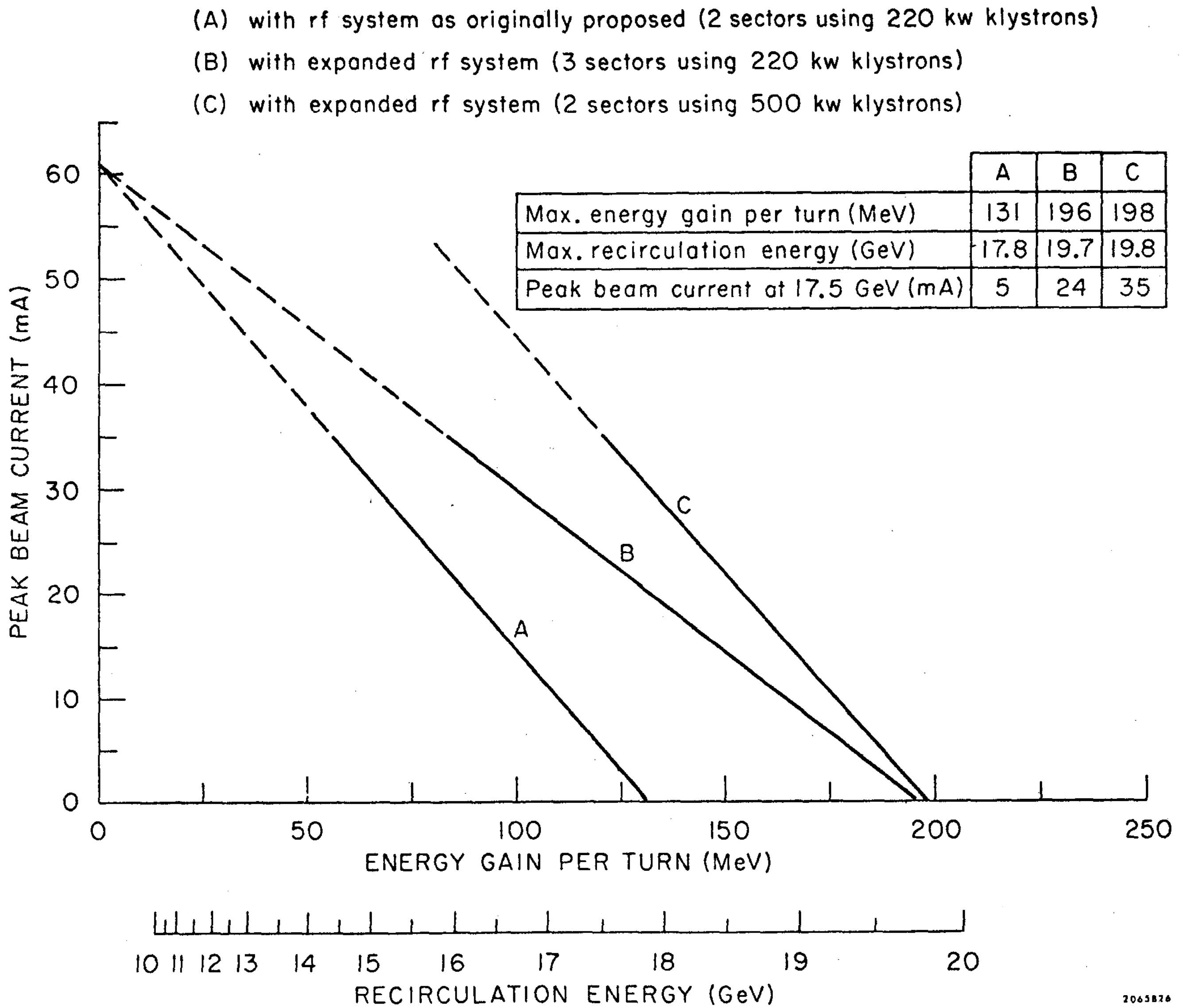


Figure 2. SLAC energy growth.



	A	B	C
Max. energy gain per turn (MeV)	131	196	198
Max. recirculation energy (GeV)	17.8	19.7	19.8
Peak beam current at 17.5 GeV (mA)	5	24	35

Figure 3. Load-line diagrams comparing three different RF systems. System parameters are similar to those given for Case 1 in Tables I and II at a phase angle of 30°.

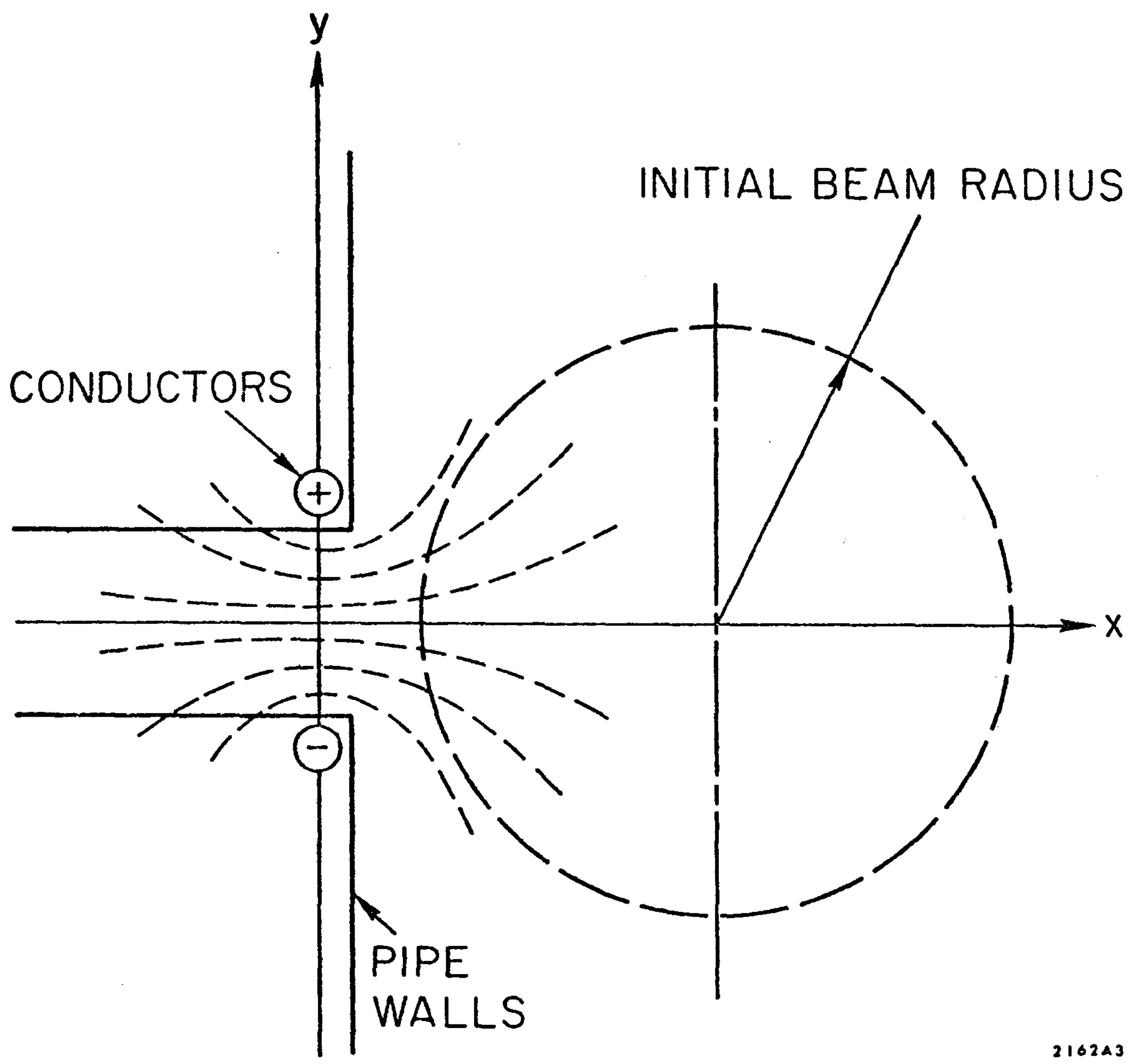


Figure 4. Bifilar loop for magnetic perturbation suitable for a long spill extraction device.

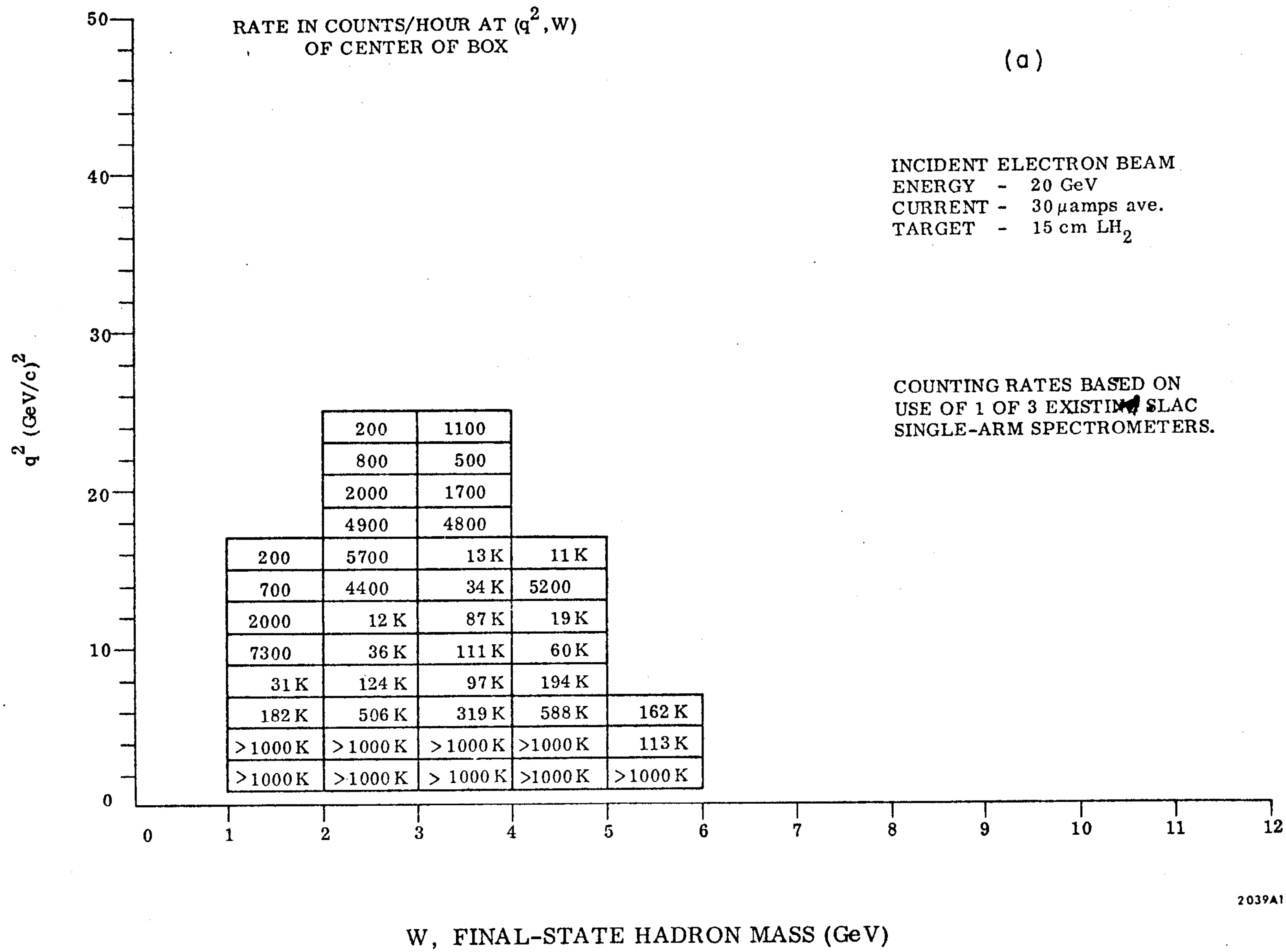


Figure 5. Expected counting rates for inelastic scattering using single arm spectrometers with the present SLAC accelerator (a) and RLA (b).

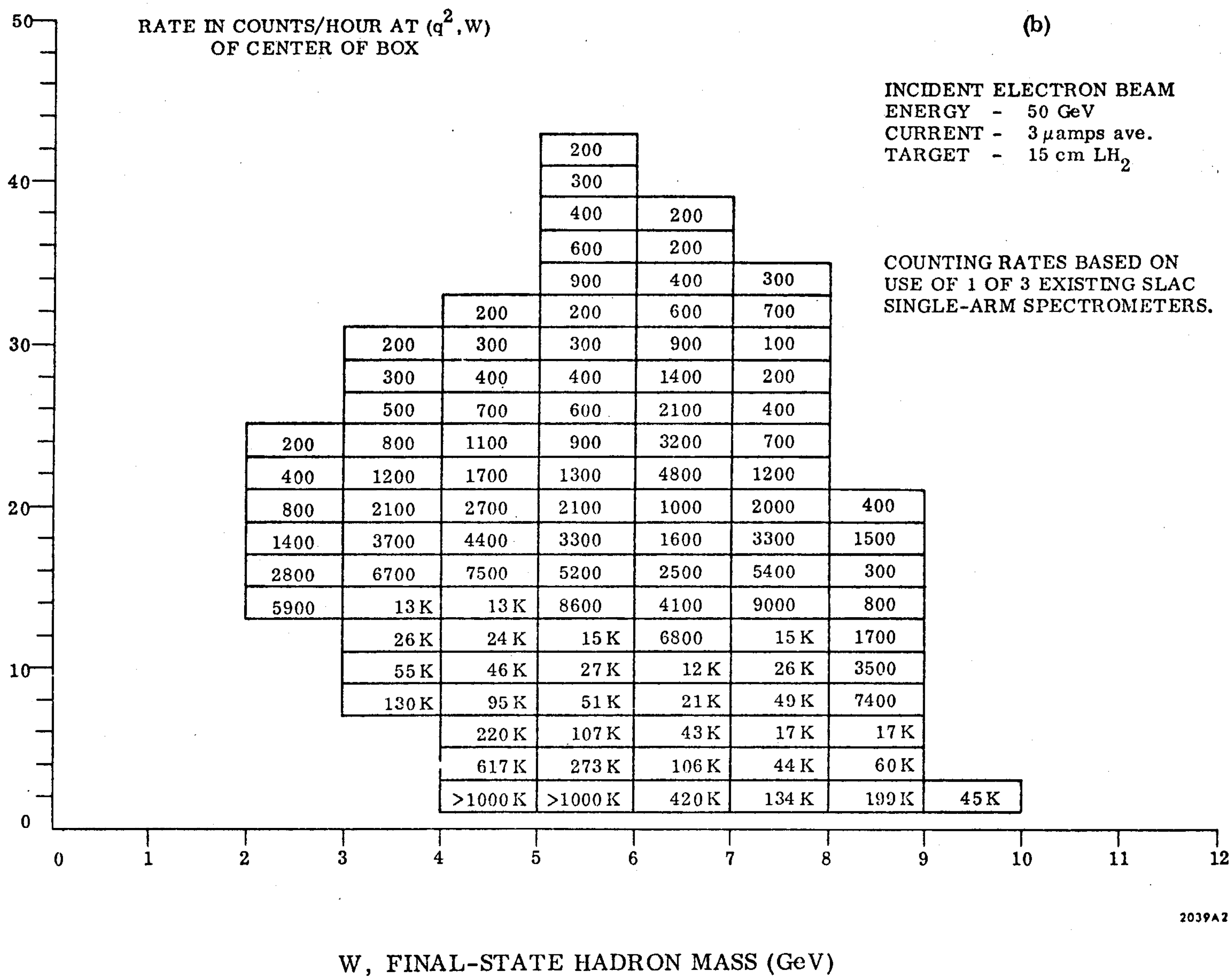


Figure 5 (continued).