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Amended Proposal for R&D on a Cluster Klystron

R.C. Fernow, J. Fischer, J.C. Gallardo, H.G. Kirk, S.K. Ko
R.B. Palmer, S. Ulc and H. Wang

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1) Introduction

This Proposal is an updated version of FWP submitted in March 1992. Significant work has been done since the original proposal, and much of this is reported on in this update. In addition there have been several changes made, some in response to suggestions made by the three reviews sent to us in December, 1992.

The new information and changes include:

- 1) Technical information on the proposed design of the magnetron gun (sec. 9.1), the magnet (sec. 9.4), acceleration gap (sec. 9.5), and electrical system (including a comment on efficiency loss due to high-voltage leakage current) (sec. 9.7).
- 2) Modification of the phase I and II tests to allow operation of the gun and klystron off the axis of the magnet, thus simulating the magnet situation when multiple beams are used (sec. 7.2).
- 3) Modification of phases III and IV to test a cluster of three beams: first a three beam gun, and then three beams with a klystron on one of them. We have added a phase V which would be the testing of a full three-beam demonstration klystron (the phases are described in sec. 7.2).
- 4) The mod-anode pulser would now be located on the high voltage deck instead of externally. Power for the pulser and other high voltage components would now be provided by an isolation transformer instead of from a lead battery. See sec. 9.7.

We believe these changes have improved the proposed program and thank the reviewers for their constructive suggestions. The design is still evolving. Relatively little work has been done on the detailed klystron design, and none on the beam dump. We apologize for remaining inconsistencies between engineering sketches and computer simulation output.

2) The Immersed Field Cluster Klystron Concept

The proposed device (ref. 1) consists of a "cluster" of low current moderate power klystrons, supplied by a common high-voltage source, and contained within a common focussing field. The electron guns would be of the "magnetron injection" type, operating in the same field as the klystrons. Because these guns are very compact, the individual tubes can be quite tightly packed (2.6 cm spacing for the proposed 11.4 GHz klystron). Because the magnetron injection guns have a relatively low voltage (50 kV) annular electrode, these can be used as mod-anodes to switch the beam currents. The main accelerating field can then be provided by a dc 400 kV supply.

It is believed that the proposed device, if practical, would achieve efficiencies (from wall plug to rf) approximately a factor of two greater than any other current power source suitable for linear colliders. Since the expected power requirements of such colliders are very high, the development of more efficient sources could have a major cost impact.

The expected improvement in efficiency would be obtained from:

a) higher individual klystron efficiencies due to the lower beam currents (and thus perveance) in the individual beams;

b) the lack of the need for a pulsed modulator because of the use of a mod- anode. As a result we avoid most of the power waste during the slow rise and fall of the conventional modulator ; and

c) the use of less pulse compression, and thus shorter rf pulses, without a corresponding loss of modulator efficiency, again because of the use of a mod-anode.

3) High Energy Physics Need

Current SLAC and KEK plans for a Next Linear Collider (NLC) call for an initial center-of-mass energy of 0.5 TeV with a later upgrade to 1.0 TeV. They both propose to use conventional rf linac structures operating at a frequency of 11.4 GHz. The SLAC proposal is for an initial accelerating gradient of about 50 MeV per meter, with the energy upgrade obtained by increasing this gradient to approximately 100 MeV per meter. Estimates of efficiencies and power consumption, taken from the SLAC proposal for a "A Test Accelerator for the Next Linear Collider" (ref. 2), are given below.

Center of Mass Energy	TeV	.5
number of klystrons		3890
power per klystron	MW	50
modulator efficiency	%	73
klystron efficiency	%	45
rf pulse compression	x	6
compression efficiency	%	67
distribution efficiency	%	86
wall-rf eff.	%	19
rep rate	pps	180
wall power	MW	160

This initial gradient does not result in a very demanding requirement for the rf power sources, and conventional klystrons may suffice, although even in this case there are questions about efficiency (160 MW is high) and the cost of the modulators.

The upgrade to 1 TeV by doubling the accelerating gradient requires a four-fold increase in rf peak power and modulator stored energy. If the luminosity is to rise to maintain fundamental event rates, then the repetition rate must be maintained (there are also tolerance reasons for maintaining it). If this is done, and the other parameters remain the same then there would be a four-fold increase in wall power consumption. From 160 MW, the power would rise to 640 MW! Some reduction in event rate may be acceptable, but clearly a significant improvement in efficiency is also required.

An additional problem may be the cost of the modulators. With present designs the modulators account for more than half of the rf source cost, and could be the single largest cost in the entire project. Anything that might reduce this cost should be investigated.

The requirement then is for a source of rf power for the 1 TeV upgrade of a Next Linear Collider. With 6 x pulse compression (as proposed by SLAC) the units should each give 100 MW, for 1.5 microsecond pulses; but if 4 x compression were preferred to improve the efficiency (as proposed here) then the power per unit should be raised to about 150 MW or the pulses reduced to 1 microsecond. An overall power efficiency of double the projected 19% seems a reasonable goal.

4) Historical Background

The basic idea of a cluster of klystrons using conventional Pierce guns was proposed and implemented 30 years ago (ref. 3), and has been proposed more recently for this application (ref. 4). But these designs require separate magnetic field shaping for each of the guns resulting in a difficult magnet design. In addition the Pierce guns set a relatively large spacing between beams, resulting in a bulky package.

The new idea presented in reference 1 was to use magnetron injection guns that can operate in the same magnetic field that guides the electrons down the klystron. With this modification, the multiple beams of the cluster could be placed quite close to one another, the cluster would be compact, and all could share a common focussing field.

The idea of the magnetron injection gun is also old (ref. 5), and has also been used in commercial tubes. Mod-anodes have also been used in commercial devices for a long time. Thus the proposed cluster klystron does not involve any new invention. Rather it is the bringing together of proven ideas to solve this particular problem.

The cluster klystron described in reference 1 was aimed at the Linear Colliders of the far future. It addressed the ambitious goal of providing 1 GW of power with a wall plug to rf efficiency of over 50%. On paper this was achieved, but at the price of significant complexity. The device had 42 individual tubes, and employed coupled cavities. For the requirements of a "Next Linear Collider", clusters of 6 (or even 3) tubes would suffice, and for this the cavities of the beams do not need to be coupled inside the klystron.

5) Parameters of Proposed Demonstration Tube

We propose to do the needed R&D to establish the practicality of a cluster klystron suitable for the NLC that would consist of 6 individual klystrons. We are not proposing to build that tube now, but we would, in the last phase, build a three tube "demonstration model" (Fig. 1), whose parameters, together with those for the NLC tube, are given below:

		<u>for NLC</u>	<u>model</u>	
Anode Voltage	(kV)	400	400	
Cathode current density	(A/cm ²)	36	36	
Current/tube	(amps)	100	100	
perveance	(micropervs)	.42	.42	
efficiency	(%)	65	65	note 1
output power/beam	(MW)	26	26	
number of beams		6	3	
total output power	(MW)	156	78	
pulse duration	(microsec)	1.0	0.25	note 2
beam energy	(J)	6 x 40	3 x 40	
beam energy density	(J/cm ²)	62	62	note 3
rep rate	(pps)	180	30	note 2
modulator efficiency	(%)	88	80	
modulator energy/pulse	(J)	266	27	
pulse comp. efficiency	(%)	80	-	
distribution efficiency	(%)	86	-	
wall-rf efficiency	(%)	39	-	

Note 1: In ref. 1 it was noted that at such a very low perveance, an efficiency over 70% might be expected, and a simulation achieved this performance. But for this proposal we take 65% as a more conservative goal. Whatever the actual value achieved, it is reasonable to assume a substantially better efficiency with a perveance of 0.42 compared with the value of 1-2 for conventional tubes.

Note 2: The pulse length of the model could be later increased to 1 microsecond by replacing the high voltage pulse forming cables in both pulser and 400 kV circuits. The repetition rate would then be 10 Hz.

Note 3: Assuming a beam diameter of 9 mm. This energy density (62 Joules/cm²) is less than that in a SLAC S-band 50 MW klystron (90 Joules/cm²), and does not melt copper if it hits the klystron wall. In contrast the high current beams of conventional X-band tubes do melt copper, thus making their development difficult and the tubes intrinsically less reliable.

6) Collaboration

The proposed R&D would be carried out by a collaboration between Brookhaven Lab and SLAC, with industrial participation.

This work would be a part of the activities of the BNL Center for Accelerator Physics (CAP), which is an interdepartmental organization with the mission to promote research and education in accelerator physics and technology. The work is receiving support from the Laboratory, both through this organization and through an approved Exploratory Research Grant.

Staff now involved in the project are listed below, together with the approximate percentages of their time on this project.

			<u>up to now with funding</u>	
R.B.Palmer	Physicist	SLAC/BNL D.O.	60%	60%
H.P.Wang	Acc. Engineer	BNL Physics	100%	100%
R.Fernow	Physicist	BNL Physics	10%	50%
H.Kirk	Physicist	BNL Physics	25%	75%
J.Fischer	Physicist	BNL Inst.	10%	30%
S.K.Ko	Physicist	BNL visitor	100%	100%
K.Batchelor	Physicist	BNL NSLS	-	10%
S.Ulc	Mech. Engineer	BNL Physics	50%	50%
Additional post doc	-	BNL Physics	-	100%
W.Herrmannsfeldt	Physicist	SLAC	10%	25%
R.Miller	Physicist	SLAC	-	10%
K.Eppley	Physicist	SLAC	10%	25%
T.Lee	Elec. Engineer	SLAC/BNL	25%	50%
M.Green et al.	Varian (Palo Alto, CA)			
K.J.Harker	SRI International			

Expertise of Collaboration Members

R.B.Palmer is the BNL spokesman for the collaboration. He is a Senior Scientist at BNL, an Adjunct Professor at Stony Brook, and a Physicist at SLAC. He has experience in experimental physics, advanced accelerator theory, superconducting magnet technology, and linear collider theory.

Haipeng Wang is a professional at BNL. He is a young graduate engineer with an MSc in Accelerator Physics (Stony Brook). He has experience in high voltage engineering, rf design and superconducting cavities.

Rick Fernow is a High Energy Physicist who has, for some time, been involved in advanced accelerator research. He is spokesman for the Grating Accelerator Experiment at the ATF, and has contributed greatly to the construction of the Facility.

Harold Kirk is a High Energy Physicist at BNL. He has for some years been working on the design and construction of the ATF, and is active in the experimental program there. He has experience in rf cavity simulation (MAFIA), and beam design and simulations (PARMELLA, TRANSPORT).

Joe Fischer is a Senior Physicist in the Instrumentation Division at BNL. He has long experience in many kinds of instrumentation: in high voltage pulsed electronics, nuclear particle detectors, gas media, and laser driven high field electron emission.

Seung-Kook Ko is a Professor at the University of Ulsan, Korea, and is currently visiting BNL. He is an experimental physicist with hands on experience in beam physics, ion sources, and tokomaks.

Stan Ulc is a Mechanical Engineer in the Physics Department at BNL. He has experience in precision instrumentation and has engineered beam lines and the laser acceleration experiment at the ATF.

Ken Batchelor is a Senior Physicist at the NSLS. He has designed klystrons in England, designed the BNL ATF gun, is the NSLS Safety Coordinator, and has wide experience in rf systems, electron accelerators and light sources.

Bill Herrmannsfeldt is the SLAC spokesman for the collaboration. He is a Senior Physicist at SLAC. He was a co-author of the second cluster klystron paper, has long experience in electron gun design, and many computer simulations, and is the originator of EGUN.

Roger Miller is a Senior Physicist at SLAC. He was a co-author of our first cluster klystron paper. He has long experience with almost all aspects of guns, accelerators and rf power sources.

Ken Eppley works in Bill Herrmannsfeldt's group at SLAC. He is an expert in computer simulations of beam problems in general and klystrons in particular (CONDOR). He was a co-author of the second cluster klystron paper.

Terry Lee is a senior member of the SLAC Klystron Group. He is a klystron designer with long practical experience of construction and testing of the devices. He will be retiring from SLAC in early 1993 and would then work half time for the cluster klystron collaboration.

Mike Green at Varian (Palo Alto, CA) has lead the project to design and build the high current density reservoir cathodes for this project. He is a Senior Physicist at Varian with long experience in cathodes.

Kenneth J. Harker at SRI International has done theoretical studies on the magnetron gun design, and provided the detailed parameters of the required fields for laminar electron flow. He has been under a consultant contract with SLAC. He is an expert of long standing in klystron theory and design.

As part of the collaboration SLAC has provided:

- a) A 400 kV power supply (surplus from the SLAC Lasertron)
- b) A high voltage cable (surplus from the SLAC Lasertron)

- c) A high voltage tank (surplus from the SLAC Lasertron)
- d) A 5 kG solenoid (surplus from the SLAC/Livermore Relativistic Klystron)
- e) Some purchased vacuum and other equipment

There have been discussions with Haimson Associates on a possible collaboration in which Haimson would provide the output circuit for the klystron. Haimson Associates manufactures klystrons, linear accelerators and associated rf equipment. He has recently pioneered the use of travelling wave structures as output cavities in klystrons.

There has also been discussion with David Yu of DULY Research, Inc. He will be applying for an SBIR grant to study the possibility of coupling the cavities between the groups of beams in the cluster. This would pave the way to clusters of a size much greater than the six proposed now. David Yu is a theorist with wide expertise in rf structures and simulation.

7) R&D PLAN

7.1 Questions to be answered

- 1) Will the cathodes provide the needed high current density (36 A/cm^2)?
- 2) Will the magnetron injection guns operate without instability and the resulting excessive noise?
- 3) Can the mod-anode be used to switch the required dc high voltage without excessive leakage?
- 4) Can the guns and klystrons operate off axis within an imperfect solenoid magnet and common electrostatic accelerating field ?
- 5) Can the very high efficiencies predicted by simulations for the low perveance klystrons be achieved?

Implicit in this list are a number of aspects of a final tube that are not considered to require R&D at this point:

- 1) Operation at any significant repetition rate. Since the power per beam is modest, it is not anticipated that heat dissipation at the higher repetition rate could be a problem.
- 2) The assembly of a unit with the full complement of six beams. Since the individual sub-klystrons are independent of one another, it is anticipated that if a three beam unit can be tested successfully, there will be little problem in increasing the number to six.

- 3) The use of a superconducting magnet. This, though necessary on power considerations in the final unit, should not effect the performance of the klystrons and should not require special development.

7.2 Plan Outline

Brookhaven Lab, where the program would be carried out, has expertise in developing many novel technologies, but it has no klystron facilities, klystron expertise or test stands. If we are to proceed rapidly, we must not try to do too much, and must use as much borrowed or existing equipment as possible. Thus we are not now proposing to build a cluster klystron with all features required for the Next Linear Collider. We are proposing only to test, in a phased program, those features which we believe are most uncertain. Only if these tests are successful should a real tube be developed, and that would best be done in industry.

Each phase of the plan should yield significant knowledge, and can thus be justified, even without later phases. It is recognized that later phases may have to be modified in the light of what we learn. The proposed phases are:

Phase I	Test of Single Magnetron Gun at 50 kV	(end of year 1)
Phase II	Test of Single Magnetron Gun at 200 kV	(early year 2)
Phase III	Test of Three-Beam Gun at 400 kV	(end of year 2)
Phase IV	Test a Klystron Using One of Three Beams	(mid year 3)
Phase V	Test a Three Beam Klystron	(end of year 3)

For phases I through III the repetition rate would be very low (0.2 Hz). Only in the last phases would the rate of 30 Hz be tested.

7.3 Plan Details

Phase I: Diode Test of Magnetron Gun at 50 kV (by end of year 1)

(a) Test the proposed magnetron injection gun on the axis of the SLAC solenoid magnet. One of the two available Varian dispenser cathodes would be used, with the other as a spare. Measure noise in the beam, maximum current, and beam cross section.

(b) Repeat the above with the gun moved up to 1.5 cm off the magnet axis. Study effects of field errors.

The test is important because very few guns of this type have been made and tested, and some evidence of noise or instability had been observed. Although the design to be tested is a straightforward scaling from the previous design, it is important to determine that stable operation can be achieved at the smaller scale required. It is also important to determine experimentally what effects off-axis magnetic-field errors will have on the gun performance.

Tasks: Build the mezzanine floor, mount and connect the solenoid, deionized water system and power supply. Assemble the high voltage deck and insulators. Buy the cathode bombardier supply. Build the vacuum chamber, magnetron gun, test cavity, diagnostic box and the mod anode pulser. Assemble initial diagnostics, interlocks and control system.

Phase II: Test of mod-anode switching of 200 kV (by early year 2)

Apply up to 200 kV dc across the accelerating gap and demonstrate the switching of the single beam with the pulsed mod-anode. Measure leakage current and any other difficulties associated with the use of the dc high voltage.

The full voltage of 400 kV would not be tried, because breakdown is possible in the relatively narrow radial gap between the high-voltage column and the vacuum chamber wall. This gap is smaller than in the previous proposal because of the reduced inside diameter of the vacuum chamber (to allow operation both on and up to 1.5 cm off the axis). Breakdown is also more probable than in phase III and beyond because, with the unmodified solenoid, there is only 1 kG axial field to magnetically insulate this space.

Tasks: Build and assemble the high voltage dome and pressure tank. Connect the power supply, build the cage and safety interlocks.

Phase III: Test of three-beam gun at 400 kV (end of year 2)

The three beams would be in a triangular pattern, 2.6 cm apart and thus approximately 1.5 cm from the magnet axis. A test at full voltage should now be possible since the vacuum vessel will have the full diameter, and the final magnet design, having no iron end pole, will give a 3 kG field to magnetically insulate between the stalk and vacuum chamber.

The test will observe one of the beams after the acceleration gap and determine if any deterioration in beam quality has been produced by the non-axial electrostatic accelerating fields. By turning the other beams on and off, the interaction between beams would be studied. *Tasks:* Construct the three beam gun assembly using the three available Varian Reservoir cathodes. Order spare Varian cathodes. Build a new full diameter vacuum vessel. Purchase and assemble the new magnet end coils and iron return. Modify the electrical system to supply the three guns. Build a new diagnostic box. Assemble SF_6 gas system.

Phase IV: Operation of one klystron, using the three beam gun (mid year 3)

Test a single high-efficiency klystron. This test should establish the very high efficiency (of the order of 70%) possible with the low perveance of the proposed tubes. More than one such test may be required before such high efficiency is achieved.

Tasks: Build a high-efficiency klystron, with multiple bunching cavities and a travelling wave output circuit. Build a beam dump. Provide equipment for rf supply, a Travelling Wave Tube amplifier and output rf diagnostics.

Phase V: Test a cluster of three klystrons (end of year 3)

The individual circuits can be identical to that tested in phase IV. A test would be made of a hybrid to merge the three tubes. Efficiency would be studied as a function of unequal performance of the three tubes.

Tasks: Construct a three klystron assembly. Increase the input power source. Design and build a hybrid to combine the three outputs.

8) Description of Apparatus

A test stand would be constructed in the Target Room III of the Tandem Van de Graff. This room (Fig. 2) has approximately 200 square feet of floor space, a 22 foot ceiling and has 4-foot concrete walls. Apart from the presence of some power supplies the room will be available solely for this project. The offices and labs of the group, which have recently been moved, are nearby.

The test stand would consist of the components listed below. Figure 1 indicates the main components. Figures 3 (a) and (b) show some details of the stand configured for phase I and II. Figures 4 (a) and (b) show the stand configured for phase III.

- 1) The SLAC 400 kV power supply. This is a 7.5 mA, 0-400 kV supply, consisting of a 6 foot high vertical stack operating in air. The supply was used for the SLAC Lasertron Project and has been provided to us by SLAC. It is now in Target Room III.
- 2) A high voltage cable approximately 77 feet long that serves two purposes: a) it connects the power supply to the klystron, and b) it serves as a pulse forming network (PFN) to supply klystron pulse current at constant voltage for 250 nsec. Most of the cable, which is approximately 2 inches in diameter, will be in a 7 foot diameter 3 turn coil.
- 3) An 8 foot high, 12 foot by 12 foot, steel mezzanine with 20 foot high "A" frame lift above it. The klystron will be mounted vertically through this mezzanine, with the high voltage tank above it and the solenoid magnet, klystron cavities, and beam dump below it.
- 4) A pressure tank capable of holding gas at 3 atmospheres pressure. Inside the tank, at its base, a 12 inch diameter, 18 inch high, double insulator will support a "high voltage deck", covered by a dome, that will be held at 400 kV DC. The tank will initially be filled with 3 atmospheres of a nitrogen/CO₂ mixture. Only if this is found to be inadequate will SF₆ be employed. A shorting bar would be used to assure discharge before opening the tank.
- 5) A 15-50 kV, 250 nsec thyatron pulse modulator, mounted on the high voltage deck, would be used to control the modulated anode and thus switch the beam current. The voltage of the pulse would be controlled by a fiber optic digital link.

- 6) A high-voltage isolation transformer would be employed to provide power for the pulser, the cathode heater and a 1 kV power supply to power the cathode bombarder current and to bias the cathode. The bombarder voltage and bombarder cathode on/off would be digitally controlled through optical fibers.
- 7) The magnetron injection gun (or guns) would be water cooled and supported on the end of an approximately 30 inch long stainless steel tube pointing down from the 400 kV deck into the vacuum vessel below. The gun will consist of one or more Varian bombarder reservoir cathodes, with the mod-anode supported on three insulators in front of it. A guard ring at cathode potential surrounds the mod anode.
- 8) For phases I and II, the main vacuum vessel would consist of an approximately 11 inch diameter section attached to the bottom of the main insulators, and a 6 3/4 inch diameter extension that fits inside the upper part of the 8 inch inside diameter solenoid. The clearances allow the vacuum chamber to be on the magnet axis, or up to 1.5 cm off axis. To the larger diameter part are attached a pipe to the vacuum pumps. The magnetron gun and main accelerating gap will be in the smaller diameter section, inside the field of the solenoid. A pyrometer will monitor the temperature of the cathode and servo the cathode bombarder voltage.

For phase III, and beyond, the lower part of the vacuum chamber would be approximately 8 inches diameter, nearly filling the solenoid. There would be three magnetron guns, and three pyrometers.

The vacuum chamber should not need to be baked to temperatures higher than 200 degrees C, but would be constructed to allow higher temperatures. It would be pumped initially by a turbo pump and, maintained by two 20 liter per second ion pumps.

- 9) The solenoid would be supported from the ground, with its top level with the floor of the mezzanine. The klystron and all associated equipment would be designed such that it can be inserted and removed from the solenoid by lowering or lifting it using the "A" frame crane.

For phase I and II the SLAC 9 block solenoid will be used without modification, except that the end two blocks will be powered separately and at a higher current than the remaining 7 blocks. For phase III, and beyond, the solenoid will be extended by the addition of end coils to extend the length of good field and provide a stronger field to magnetically insulate the gap between column and vacuum tank.

- 10) The apparatus to be attached below the main vacuum vessel will change with the phases of experimentation. For phases I and II a single cavity and diagnostic box will be used. The cavity will be connected, via a bakeable vacuum window, to a crystal detector or frequency analyzer to study beam noise. The diagnostic box will contain a movable plate with Faraday cup, open hole, or lead glass screen.

For phase III diagnostic cavities would be provided for all three beams. Faraday cups would be provided on two of the beams and a movable plate with Faraday cup, open hole, or lead glass screen, provided on the third.

For phase IV Faraday cups will be provided on two of the beams and a klystron on the third.

For phase V three complete klystrons would be mounted, with beam dump below.

9) Design Details

9.1 Magnetron Injection Gun

The problem of laminar current flow in spherical coordinates in an axial magnetic field has been studied by V.W. Dryden (ref. 6). The method was applied to the flow from a conical cathode by K. Harker (ref. 7) to specify the electrode shapes for magnetron injection guns for use in a klystron. A cathode cone half-angle of 4 degrees was employed, in a constant axial magnetic field. Two guns were designed and built to this specification (ref. 5). Figure 5 shows the dimensions of the cathode and electrode shapes for differing perveances. Figure 6 shows the beam shape as observed on a tungsten screen.

One of the two test guns was employed in a six gap L-band klystron. The klystron had a micropervance of 7, a gain of 37 db, an output power of 12 MW at an efficiency of 33%. Noise was not a problem at the design voltage and magnetic field, but became very bad when the voltage was lowered from the design value by 30%. The same basic design was also used in a standard Eimac cw klystron, where the outer gun electrode was used as a mod-anode. In these tubes an efficiency of 40% was obtained, with a noise ratio of 60 db.

We are using the same design methods as employed in these previous tubes. The shape, potentials and gradients at the beam boundaries, as a function of beam time, are obtained from the theory of Harker (ref. 7), and fitted to polynomials (Fig. 7). The electrode shapes are then found, again by Harker's method, from these polynomial solutions (Fig. 8).

We have selected the somewhat larger half-angle (6.28 degrees) than that used in Reference 5 (4 degrees). This should reduce the likelihood of noise problems. Figure 9 (a) shows our calculation of beam trajectories, which may be compared to those calculated by K. Harker as shown in Fig. 9 (b). They are very similar up to the coordinate axial distance=0 (the point of the conical cathode if extended). Beyond this point the calculation is not relevant since the beam has then entered the accelerating gap and the spherical symmetry required by the theory is no longer present.

EGUN (ref. 8) simulations of the gun (Figure 10) do not show the laminar flow predicted by the theory and presumably present in the klystrons referred to above (Ref. 5). This is probably the result of limits on the mesh size and possibly on the intrinsic stability of the EGUN space charge calculation. Nevertheless, the failure to obtain laminar flow

in EGUN simulations leaves us less than comfortable. For this reason we have given high priority to the testing for noise in the gun (phase I).

9.2 High-Current Cathode

Since a magnetron injection gun is immersed in a strong magnetic field (4kG), electrons from the cathode move in relatively straight lines parallel to the axis. The only area compression between the cathode and beam comes from the small angle of the cathode cone (6.28 degrees giving an area compression of approximately 9). A smaller angle would give a larger area compression, but greater danger of instability and noise. As a result of this low area compression, a relatively high current density (approximately 40 amps/cm²) is required.

In 1989 when ref. 1 was written, the requirement of a high current density on the cathode, coupled with the need for a lifetime of the order of 10,000 hours was considered to be the greatest developmental problem in the cluster klystron. Accordingly an R&D contract was signed with Varian. This contract was funded by DOE through Brookhaven National Lab and is now complete. Two shorter life dispenser cathodes and three final reservoir cathodes have been delivered.

The design of the delivered cathode systems is shown in Fig. 11. It consists of a porous conical cathode, coated with osmium for low work function. The cathode is fed with barium oxide from an annular reservoir. The cathode and reservoir are heated by radiation from an inner cone that is in turn heated by electron bombardment from a secondary low current gun at the rear. The system is relatively complicated, but it is believed that it should not only meet our requirements, but may well be capable of significantly higher current densities than specified. We are assured that the unit cost in mass production should not be excessive.

Under our conditions, with a good osmium cathode, a current density of 40 A/cm² should require a temperature of 1070 deg.C (ref. 9). With a conventional cathode, the lifetime at this temperature would be only about 2000 hours. For such cathodes the life is limited by: a) the loss of active chemicals within the porous tungsten matrix that are generating the active barium oxide, and b) the diffusion of the tungsten into the osmium surface layer causing a loss in its role of supporting the monolayer of barium oxide in the correct polarized state. Varian has developed solutions to both limits: the barium oxide is generated from a reservoir external to the cathode surface, and some special barrier is used to stop the tungsten diffusion. With these improvements they believe that the delivered cathodes operating at 1070 degrees C should have a lifetime of at least 10,000 hours. This prediction has been confirmed in the life test of a small planar cathode, made for NASA, which uses the same technology as applied to the cathodes supplied to BNL for this project.

9.3 Magnet Requirements

Since the electrons will travel approximately along the field lines, the requirement for off axis operation is that these lines be straight to within a fraction (say 1/10) of the designed space between the beam and drift tube radii (.5 mm). The field lines must thus be straight to $\pm .05$ mm. This specification translates into a requirement on the uniformity of the axial field of $\pm$ a fraction $f = 2 \times (0.05 \text{ mm}/r)$, where r is the distance from the axis. At a radius of 1.5 cm this requires the axial field to be constant to $\pm 0.7\%$, or ± 30 Gauss at 4 kG.

In addition, the angle of the field lines in the gun region should be very small (say 1/50) compared with the cathode cone angle (6 degrees). Thus the angles should be less than 0.12 degrees (2 milliradians). For an axial field of 5 kG, this corresponds to an acceptable transverse field component of 10 Gauss.

For the gun tests in phases I and II, the length over which the good field is required is approximately 28 cm (3 cm for the gun, 10 cm for acceleration, 5 cm for cavity, and 10 cm for diagnostics. For the klystron, the good field length required is at least 66 cm (3 cm for gun, 10 cm for acceleration, and 53 cm for the klystron design referred to below).

The above specifications are only estimates. They can only be confirmed by a full 3 dimensional simulation, or by experiment. We will use the program MAFIA V3 (ref. 10) to simulate some aspects of the problem, but only experiment can give a clear answer as to whether these specifications are adequate.

9.4 Magnet Designs

Several magnet configurations have been designed using the program INTMAG (ref. 11):

- 1) The solenoid, as provided by SLAC and powered uniformly in all pancakes gives fields as shown in Fig. 12 (a). The axial field is sufficiently constant over the length required for phase I and II (a) on axis gun tests. However the good field length at 1.5 cm from the axis [see Fig. 13 (a)] is only 20 cm. (Note that the transverse field (BVr) is 10 Gauss at $x = -10$) This is not good enough even for the phase I and II (b) off axis tests.

- 2) If the end pancakes are separately powered with a current 39% higher than the rest, then the fields at 1.5 cm are as shown in Fig. 13 (b). The good field now extends over a length of 36 cm, starting 12 cm from the end. The field at the vacuum chamber transition from 6.75 inch to 11 inch diameter would be approximately 1 kG in this case. This magnet meets our requirements for phases I and II, but the good field length is not sufficient for klystron tests. Also, the 1 kG field at the transition may not be sufficient to magnetically insulate the 400 kV between the high-voltage column and the vacuum chamber.

- 3) If two new coil blocks are added at the ends of the existing SLAC solenoid, and new iron is added, the magnet and fields are as shown in Fig. 12 (b). The fields at 1.5 cm from the axis are shown in Fig. 13 (c). The field is good over a length of 70 cm, starting only

6.5 cm from the magnet end. The field at the vacuum chamber transition from 8 inch to 11 inch diameter is now 3 kG and will provide good magnetic insulation.

This design uses the same current in all blocks (314 Amps). Balance between end and central field can be obtained by moving the end blocks axially, or by adjusting the currents in the end blocks.

In a production klystron, the six beams would be at 2.5 cm from the axis and a better field quality would be required. This would occur naturally if a superconducting magnet were employed, since the coil ID would have to be larger to allow space for the cryostat. Finer tuning of the design would also give better field quality.

9.5 Accelerating Gap

In a single beam design there is little field quality requirement on the accelerating gap. However for phases III and beyond the beams pass through this gap off axis and can experience transverse electric fields. The effect of these fields has been studied using EGUN (ref. 8). We initially assume a perfectly constant 4 kG magnetic field and no space charge. If the geometry of phases I and II were used with three beams then the center and limiting trajectories of the beams would be as in Fig. 14 (a). Little effect is seen in this figure, but there are significant azimuthal displacements to the beam center [Fig. 15 (a)]. While the beams remain in the gap, these are of no consequence, but the final value of approximately 40 mrad (0.6 mm) is significant. This could in principle be corrected by rotating the three klystrons with respect to the guns, but this is unsatisfactory. Instead we propose a guard ring around the mod-anode [Fig. 14 (b)] which can be so placed as to correct this displacement [Fig. 15 (b)].

The gap is 10 cm long, which should not be likely to break down even at 400 kV. If it does, then the guard ring serves a second important function: the breakdown is likely to go to the ring rather than to the mod anode, thus giving some protection to the mod-anode pulser circuit.

In addition to the azimuthal effect the changes of the transverse fields introduce an increase in beam emittance. The beam size is increased by an acceptable 0.1 mm, and an acceptable angular spread of 25 mrad is introduced (cf the spread caused by the non-laminar EGUN calculation, and used by CONDOR, was 100 mrad).

In Fig. 14 (c) and 15 (c) the radial and azimuthal trajectories are given with the magnetic fields calculated by INTMAG. As expected, no significant difference is observed.

Fig. 14 (d) and 15 (d) show the radial and azimuthal trajectories with space charge turned on. Because this is a 2D program the calculation is for one 300 A annular beam, rather than three separate 100 A beams, but in the open gap the beam forces should be approximately correct. The observed effects give acceptable displacements of less than 0.1 mm. Some small effects, which would not exist in the real situation, are also seen in the

region of separate beam pipes. This is to be expected since the program is here calculating an annular space, rather than separate tubes.

9.6 Klystron Design

Fig. 16 (ref. 12) gives the efficiencies of some operating klystrons versus their perveances ($= I/V^{3/2}$). It shows the well known correlation between them. The perveance of each beam in the proposed cluster (at 100 Amps and 400 kV) is only .4 micropervs. From the figure one should expect a tube with this value to have an efficiency of about 70%. The fact that the beam is hollow in our case should further raise this value. But since we will be calculating with the very poor initial beam emittance calculated by EGUN, a somewhat lower value is possible.

We have made several studies using the two dimensional particle in cell code CONDOR (ref. 13). A relatively conventional design with two bunching cavities and two outputs gave an efficiency of approximately 63%. Several more complicated multicavity designs with six bunching cavities and a six gap travelling wave output structure gave kinematic efficiencies of 75% and power efficiencies of 70%. Fig. 17 shows the ac current along the length of the tube. This CONDOR run was made including the large emittance calculated from the EGUN non-laminar simulation of the magnetron injection gun. Even higher efficiencies would be obtained if the predicted laminar flow was assumed.

The parameters of one of these simulations is given below:

Frequency	(GHz)	11.4
Drift tube rad	(mm)	5.0
Number of Cavities		7 + 5(TW output)
Current	(A)	100
Voltage	(V)	400,000
Beam Power	(MW)	40
Perveance	(microperv)	0.4
Focus field	(kG)	4.0

Cavity	1	2	3	4	5	6	7
Pos (cm)	0	20	25	30	35	40	45
Volts (kV)	38.5	11	11	22	44	55	71.5
Phase(-rad)		1.4	1.4	1.48	1.5	1.52	1.52
Power (MW)		.06	.07	.11	.22	.18	.25

TW output cavities					
Cavity	3	9	10	11	12
Pos (cm)	50	50.75	51.5	52.25	53
Volts (kV)	132	132	154	176	77
Phase(-rad)	.54	.54	.58	.52	- .14
Power (MW)	7.77	7.19	7.12	3.58	1.47
27.13					

Kinematic efficiency 75%

Total rf efficiency 70%

How reliable such a simulation is in this case is not known. The program correctly predicts the efficiency of tubes such as the SLAC 5045 klystron, but that tube has parameters very far from these.

This is not yet a real design. The losses in the bunching cavities are too great, and gain cavities are needed. It is also not clear that so many bunching cavities are necessary. Much further work is needed.

9.7 Electrical

The impedance Z_k presented to the high-voltage line by the cluster of three 100 amp klystrons would be $400,000 \text{ V} / 300 \text{ A} = 1333 \text{ ohms}$; plus the series resistor $R_s = 40 \text{ ohm}$, to make 1373 ohms . If $400,000 \text{ V}$ is required at the klystron, then V_k , including the loss across the resistor will be 412 kV . If the line impedance is Z_o , then the required initial (V_1) and final (V_2) line voltage will be:

$$V_1 = V_k (1 + Z_o/Z_k)$$

$$V_2 = V_k (1 - Z_o/Z_k)$$

For a cable impedance of 50 ohms , this gives:

Initial Voltage	V_1	427	kV
Final Voltage	V_2	397	kV

The mod-anode would have a capacitance of $100\text{-}200 \text{ pF}$ and be loaded by a resistor of 245 ohms for a time constant of $25\text{-}50 \text{ nsec}$. It is convenient to supply this from a 15 kV Blumlein PFN, switched by a thyatron, mounted on the high voltage deck. A $3.5\text{:}1$ step up transformer would be used to obtain the required 50 kV . The impedance at 15 kV is then 20 ohms , and each of the PFNs must have an impedance of 10 ohms . Fig. 18 shows a conceptual circuit diagram of this pulser.

A schematic of the electrical components to be mounted on the high-voltage deck is shown in Figure 19. The total electrical power required on the deck is estimated in the table below. The total power at 110 V, for the 3 gun model is 710 Watts, for which a 1 kW isolation transformer will be adequate. For a Next Linear Collider six-gun version the power would be approximately 1 kW.

	output (W)	input (W)	NLC inpt (W)
Electron gun filaments (2.5 A x 6.3 V x 3)	50	70	140
Cathode bombarder (1 kV x 30 mA x 3)	90	110	220
Mod-anode pulser (15 kV x 10 mA)	150	200	200
Pulser thyatron filament (20A x 6.3 V)	130	170	170
Pulser trigger system	20	30	30
Mod-anode bias (200 V x 5 mA)	1	10	10
Fiber optic links	50	70	70
Cooling fan	—	<u>100</u>	<u>100</u>
	491	710	980

The efficiency of the high voltage electrical system for an NLC six gun device will be determined by:

- (a) the efficiency of the 400 kV dc power supply (which could be 95%).
- (b) the rise time of the mod-anode pulser. If this is 30 nsec, then for a 1 microsecond pulse this contributes a loss of 3%.
- (c) the leakage of the high-voltage system. Contributions would come from: the power supply, cable terminations, cable, main insulator, bleeder resistor chain, insulators holding the high-voltage deck, corona in the tank, corona in the vacuum, and fiber links. The total is estimated to be approximately 1 mA. Thus, for an NLC six beam tube (6 x 100 Amps, 180 Hz, 1 microsecond pulses), this would represent a 1% loss.
- In its Lasertron configuration, the insulators, column and accelerating gap had a leakage of approximately 3 mA (133 $M\Omega$), mostly due to corona in the vacuum. In our case it should be far less than that because 1) the accelerating gap in this proposal would be almost a factor of two greater than in the Lasertron, and 2) there would be strong magnetic insulation, which was not present before.
- (d) Power consumption of the components on the deck: approximately 1 kW for the NLC case. This represents a 2.5% loss.

The overall efficiency of the electrical system would thus be $(.95 \times .97 \times .99 \times .975)$ 88.5%.

10) Safety

A safety study has been initiated and preliminary reviews by the Tandem Van de Graff Safety Committee have already been made. A more thorough study is being prepared for review by the Laboratory's Safety and Environmental Protection Division.

Safety issues include:

- Radiation—Nuclear activation is not possible but shielding will be required to insure that x-rays generated by the stopping electrons are contained. Preliminary calculations based on a 3 beam klystron operating at 30 Hz indicate that 15 radiation lengths of shielding will be required around the klystron beam dump. This shielding will be provided by lead and concrete. The shielding should be sufficient to allow operation of the klystron from a control area within the same room.
- 1) High-voltage—The 400 kV power supply will be enclosed in an interlocked Faraday Cage. Interlock schematics will be reviewed by the Laboratory.
- 2) Structural— The mezzanine loading as well as the floor loading resulting from the shielding will be reviewed by the Tandem Van de Graff mechanical engineer.
- 3) SF₆—A special gas handling system will be purchased. Detectors will be installed to identify leaks.
- 4) RF power—Shielding will be provided to insure that neither personnel nor sensitive equipment located with the room are exposed to disrupting radiation.

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Figures

1. Sketch of the three beam model klystron as configured in phase V.
2. Plan of target room with layout of experiment.
3. Details of components for Phase I and II; (a) Vacuum chamber, gun, diagnostic box and magnet; (b) Details of gun. (Note that in this figure the guard ring around the cathode is not indicated.)
4. Details of components for Phases III; (a) Vacuum chamber, gun, diagnostic box and magnet; (b) Details of gun. (Note that the magnet shown is of the phase II design. This would be acceptable here, but we would plan to use the newer design with larger end coils.)
5. Dimensions of the cathode and electrode shapes for differing perveances, as shown in ref. 5.
6. Beam shape observed in ref. 5 on a tungsten screen.
7. Beam boundry parameters as a function of beam time: (a) radius, (b) axial distance, (c) voltage, (d) perpendicular field.
8. Outer electrode shape calculated by the Harker method.
9. (a) Beam trajectory calculated for this design.
(b) Inner and outer bounds of laminar flow as calculated by K. Harker.

10. EGUN simulations of the gun.
11. Schematic of the Varian High Current Reservoir Cathode.
12. Cross section and field lines for (a) the solenoid, as provided by SLAC, powered uniformly in all pancakes; (b) the solenoid with added end coils.
13. The axial (continuous line) and transverse (dashed line) fields at 1.5 cm from the axis for (a) the solenoid, as provided by SLAC, powered uniformly in all pancakes; (b) the solenoid with 39% higher current in the end coils; (c) the solenoid with added end coils.
14. Equipotential and limiting beam trajectories calculated by EGUN for a beam with center 1.5 cm from the axis for a) the accelerating gap geometry used in Phases I and II; b) if guard ring at cathode potential is introduced around the mod-anode, and the anode shape is modified, and (c) with the same guard ring but assuming the magnetic field calculated for the real magnet by INTMAG; (d) with the calculated field and space charge forces present.
15. Azimuthal position of the beam center as a function of axial position across the accelerating gap for a) the gap geometry used in Phases I and II; b) If guard ring at cathode potential is introduced around the mod-anode, and the anode shape is modified; and (c) with the same guard ring but assuming the magnetic field calculated for the real magnet by INTMAG. (d) with the calculated field and space charge forces present.
16. A plot of the efficiencies of some operating klystrons versus their perveances ($= I/V^{3/2}$).
17. The ac current as a function of the length along a possible high efficiency klystron design.
18. Conceptual circuit diagram of mod-anode pulser.
19. Schematic showing electrical components on the high Voltage deck.

Fig. 1

Fig. 2

Fig. 3(a)

Fig. 3(b)

Fig. 4(a)

Fig. 4(b)

Fig. 5

Fig. 6

Fig. 7(a)

Fig. 7(b)

Fig. 7(c)

Fig. 7(d)

HARKER EQUIPOTENTIAL SURFACES AROUND THE BEAM

Fig. 8

Fig. 9(a)

Fig. 9(b)

Fig. 10

Fig. 11

SOLENIOD MAGNET FOR CLUSTER KLYSTRON, 400A, USING MIRROR, 10/15/92
 REAL FILAMENTS = 84, SURFACE FILAMENTS = 2*279

SOLENIOD MAGNET 303/392 A, 4kG, with end coils and end iron 1/7/93
 REAL FILAMENTS = 180, SURFACE FILAMENTS = 2*343

Fig. 12

Fig. 13(a)

SOLENIOD MAGNET FOR CLUSTER KLYSTRON, Increased end block I, 1/10/93
 REAL FILAMENTS = 84, SURFACE FILAMENTS = 2*279

Fig. 13(b)

SOLENIOD MAGNET 303/392 A, 4kG, with end coils and end iron 1/7/93
 REAL FILAMENTS = 180, SURFACE FILAMENTS = 2*343

Fig. 13(c)

Fig. 14(a)

Fig. 14(b)

Fig. 14(c)

real field, with space charge

Fig. 14(d)

Fig. 15(a)

off axis trace for cluster surrounded mod anode

Fig. 15(b)

OFF AXIS TRACE FOR CLUSTER, WITH GUARD RING, REAL FIELD

Fig. 15(c)

OFF AXIS TRACE FOR CLUSTER, WITH GUARD RING, REAL FIELD, WITH SPACE CHARGE

Fig. 15(d)

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Fig. 16

Fig. 17

MOD ANODE PULSER SCHEMATIC

EXAMPLE OF BLUMLEIN P.F.N.:
 $Z_1 = 10\Omega$, $Z_2 = 20\Omega$, $Z_{OUT} = 245\Omega$
 PULSE WIDTH 200-1000ns; 15-50kV
 C_{LOAD} 100-200pf; RISETIME 25-50ns

Fig. 18

CLUSTER KLYSTRON: Block Diagram of Electronic System

Fig. 19

END

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