THE ANL 750-kV HIGH GRADIENT ACCELERATING COLUMN*

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ABSTRACT

A high gradient accelerating column has recently been installed in the ZGS preaccelerator. This operates at 750 kV across a single accelerating gap. Beam from a duoplasmatron ion source is extracted from a 1/2" diameter plasma expansion cup by the field of the main accelerating gap. Thus lens aberration is minimized by complete absence of lens elements except at the extraction surface and at the exit aperture of the accelerating tube.

Beam currents of 375 mA have been obtained. Typical operation is with a 200-mA beam pulse of 150-200 μsec duration, for which the normalized emittance is about 0.19 mrad/cm for 90% of the beam. Two electrostatic quadrupole triplets of 4" aperture focus the beam from the accelerating tube into the beam buncher, and a magnetic triplet is used for matching into the linac.

Introduction

Even before the original accelerating column for the ZGS preaccelerator was designed, consideration was given to the desirability of achieving rapid acceleration of the ion beam in order to minimize the effects of radial space charge forces. Several possible methods of establishing a high accelerating gradient were considered, none of which at that time appeared to be practical. Consequently, a conventional low gradient accelerating tube was designed for an ion beam of about 75-100 mA. It was found that by increasing the preaccelerator current to about 125 or 150 mA, a larger beam could be accelerated by the linac. However, it was discovered from emittance studies of the preaccelerator beam, that the phase space area was much distorted,[1] with evidence of serious lens aberrations. Since this fault could not readily be eliminated, a new accelerating tube design was undertaken.

Design Considerations

The objectives in the design of the accelerating tube were: (1) rapid acceleration of the ion beam, particularly in the low velocity region following extraction from the

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ion source, in order to minimize radial space charge force effects; (2) minimization of lens aberrations by elimination of lens elements in the acceleration region, insofar as that might be feasible; (3) minimization of metallic surface area exposed to the high gradient field, particularly of the cathode surface from which electron emission might occur; (4) choice of the most appropriate metal for the high field electrodes.

By planning for an average voltage gradient in the neighborhood of 100-125 kV/in., it was expected that satisfactory ion extraction from the ion source would be obtainable by means of the field in the accelerating gap, and that it would not, therefore, be necessary to use a separate extraction field with its probable aberration effects. It was also concluded from electrolytic tank measurements of the geometry planned, that with an exit aperture diameter of the same order as the gap length, aberrations in this region should not be serious. The only other place for aberration to occur is at the plasma extraction surface which must, therefore, be established in such a way as to minimize these effects. This would have to be done empirically by shaping the extraction geometry and by controlling the plasma density by means of ion source parameters. Thus, the accelerating system would have only a single accelerating gap and no controls except for the accelerating gradient, which would be fixed by the gap length.

Description of the High Gradient Column

A drawing of the column assembly is shown in Fig. 1. The external pressure vessel of dielectric (General Electric "Herkolite") is 40" i.d., 42" o.d., and 60" long in the field region. It is capable of pressurization to 50 psiG with an insulating gas to prevent voltage breakdown across the ceramic sections of the accelerating tube. Since it is possible to operate without internal arcing with N_2 at pressures of 35-40 psiG, it has been unnecessary to use SF_6 or any other gas additives. In fact, the column has been operated at 750-800 kV with only 20 psiG of N_2 and with only occasional arcing in the pressurized region.

Shield rings, both inside and outside the pressure cylinder, define equipotential surfaces whose potentials are established by a water resistor which spirals around the cylinder between the two sets of external shield rings. The gaps between the external shield rings will each withstand approximately 150 kV dc. External arcing will therefore be initiated only by voltage transients resulting from disturbances in the vacuum region of the accelerating tube. In such cases, single or multiple gap external arcing may occur.

The Accelerating Tube

The accelerating tube is supported, under an axial compression loading of 50,000 lbs, at the middle of the pressure vessel between two reentrant stainless steel cone sections, as shown in Fig. 1. A more detailed cross section of the tube design appears in Fig. 2. The vacuum envelope comprises six cylindrical sections of 85% alumina ceramic, each 18" i.d., 20" o.d., and 5" long. These are bonded with epoxy to stainless steel rings upon which the internal electrodes and shields are supported. The intermediate shields function solely to protect the ceramic surfaces from ions and sputtered metal. The reentrant cone sections, supported from the two end rings, define the single accelerating gap whose length may be changed by means of the moveable cylinder which carries the exit aperture (cathode). The inner end of the anode structure is closed by the base plate (anode) of the ion source, not shown in the figure.

All metal parts exposed to the high field region inside the tube are made of either commercially pure titanium (where welding was involved in their fabrication) or of a Ti-Al-V alloy (where only ease of machining was a consideration). The electrical breakdown and field emission properties of the two materials are not greatly different.[2] Initially, these parts were made of stainless steel which was found to produce copious amounts of X-radiation. The stainless steel parts were replaced by titanium equivalents with the greatest reduction in sparking rate and in x-ray production being noted upon replacement of the cathode ring and essentially no difference was observed from replacement of either the anode cone or the anode faceplate with titanium parts. Figure 3 is a photograph of the tube assembly and of the pressure vessel assembly. The ion source support or anode cone is shown in the right foreground and the cathode assembly at left.

Voltage Testing and Operating Experience

Some of the early voltage testing was carried out in a relatively small room at Argonne National Laboratory (ANL) using a power supply initially of 600 kV rating converted to 750 kV. This equipment was later loaned to the National Accelerator Laboratory (NAL); and subsequent voltage testing and beam studies were carried out at the NAL test laboratory, using the high voltage equipment together with the beam diagnostics system which had been greatly improved at NAL.[3, 4]

In retrospect, it can be said that the early testing was done with a vacuum system both far from clean and without adequate pumping speed. Two 1000-liter/sec sputter-ion pumps were used on the system, primarily for convenience at the NAL facility.

Much sparking occurred during voltage conditioning but no serious damage to electrode surfaces occurred during the NAL test program. When the system was installed in the preaccelerator at ANL, the same pumping system was used; but in the meantime, this system had probably become rather seriously contaminated from exposure to the atmosphere as well as from additional components installed within the vacuum chamber. Hence, the early experience after installation at ANL was discouraging, with cathode surfaces showing damage after only short periods of operation. The addition of another 1000-liter/sec sputter-ion pump made a marked improvement in operational behavior. More recently, the addition of a 10" mercury diffusion pump has improved the vacuum system considerably, particularly from the aspect of rapid pumpdown and the removal of condensibles with the liquid nitrogen trap. Modification of the middle shield to yield greater distance from the cathode and to eliminate the middle plane has also apparently rendered some improvement without affecting the beam properties.

The sparking rate of the column, after conditioning, is now rather moderate; and unless a spark occurs either during or within a period of about 30 msec preceding a beam pulse, the effect is not noticeable insofar as machine operation is concerned. Loss of beam due to column sparking is probably between 1 and 2% at this time. The longest operating period to date is three weeks, but deconditioning time since addition of the vacuum pumps is not known.

After voltage conditioning of the column, the typical level of X-radiation is in the range from 3-30 mrad/h at a distance of about 12' from the anode which by directional studies, was found to be its primary source.[5] A partial analysis of the x-ray energy spectrum indicates that it probably is produced almost entirely by 750-kV electrons, although a small fraction of lower energy electrons cannot be ruled out by these measurements.

During these observations the radiation level was found to change by a factor of two somewhat periodically, in a period of ~ 5 min. As the higher levels were reached internal sparking became noticeable followed by both internal and external arcing. The radiation level is not affected by beam if the electrostatic quadrupoles are turned on, because all beam clears the aperture of the quadrupoles and secondary electrons originating further downstream are swept out of the return path to the accelerating tube by the quadrupole field.

Beam Extraction

As noted earlier, since no controls over extraction are provided in the system, it was necessary to arrive at a satisfactory extraction geometry empirically. Several factors are involved in this problem, among which are: (1) the diameter and depth of the plasma expansion cup, (2) the magnetic properties of the metal surrounding the cup, (3) the shape of the anode face around the expansion cup opening, and (4) source aperture size and magnetic properties.

Plasma density distribution, which strongly affects the shape of the plasma extraction surface and consequently the source brightness, is a complex function of all the foregoing factors as well as of the source parameters and the extraction field at the plasma boundary. Since study of some of the foregoing factors involves fabrication and exchange of physical hardware, the effort required to achieve optimization of all factors would be prohibitively long.

Our first effort was to determine whether a ferromagnetic or paramagnetic source anode would be preferable. Since this also constitutes the anode in the accelerating gap, a material which would not be objectionable in the high field region was necessary. Stainless steel and nickel were selected for this comparison, and there was a very marked difference in favor of the nickel. Hence, nickel has been used in all except one other case in which iron was used with a facing of titanium, but in an otherwise special geometry which partly obscured its relative magnetic merits.

Two plasma cup diameters were tried in the nickel anode plate; and 0.5" diameter proved to be somewhat better than 0.625" diameter, with the cup depth .875" for both.

A third comparison was made between an anode plate which had a plane surface surrounding the expansion cup and one into which a 67° Pierce cone had been cut. The Pierce geometry proved to be far superior to the flat surface. The accelerating gap with the Pierce extraction geometry is shown in Fig. 4. The depth of the Pierce geometry was varied in three steps of 1/8" each, but without holding constant the depth of the expansion cup. Consequently, neither of these parameters can be said to be truly optimized at this time. A 1/4" cone depth is presently being used because it gives better beam properties than other depths. Moreover, in this program the face of the anode plate was of titanium mounted on the nickel anode plate of the ion source. The relative depths of the nickel and titanium portions of the cup geometry have not yet been optimized. Some additional geometries are awaiting opportunity for testing, and much more work is required to achieve best geometrical conditions.

The accelerating gap, which determines the accelerating gradient as well as the strength of the extraction field, was initially intended to be 6" with the provision for variation as dictated by experience. In the process of making some of the changes, previous to setting up the system at NAL, the gap was inadvertently set at 7" which became known only after the equipment was returned to ANL. We are now operating with the 7" gap. However, one period of operation was tried with a 6.312" gap during the time when nothing was operating well. The voltage was carried up to 850 kV and the column appeared to behave about the same as with the 7" gap. We are not certain at this time how well a 6" gap will hold up with clean vacuum conditions.

Beam Properties

The aim in the design of the accelerating column was to obtain a beam in the range of 200 mA and with an emittance area within the acceptance of the linac, viz. 20 mrad/cm. The maximum beam thus far obtained is 375 mA. Typically the beam is set at about 200 mA for which the emittance area measures 15 mrad/cm at the 90% plane, or a normalized value of 0.19 mrad/cm.

The shape of the emittance figures obtained at ANL is much different from those of the NAL tests, although the same equipment is used (except for the signal sampling and computer system). Typical results during the NAL tests are shown in Fig. 5, which indicates an undistorted phase space area, whereas the ANL results shown in Fig. 6 show aberration effects. The reason for this difference has not yet been determined. We are presently investigating the possible difference which may arise from using a single arc modulator at NAL and a double modulator at ANL for driving the cathode and intermediate anode of the duoplasmatron source. Figure 7 shows the only results thus far obtained with the single modulator at ANL, which appears to have less phase space distortion than that from the double modulator shown in Fig. 6.

The beam from the accelerating tube enters a quadrupole triplet 12-1/4" from the end of the accelerating gap. A second triplet in the beam line matches the beam through the buncher and a third triplet beyond the buncher matches into the linac. The attempts to calculate a best match through this system have not achieved the desired results. At present we can boast of only about 25% increase in beam through the linac and into the ZGS. Maximum beam to date under stable conditions is 33 mA from the linac, with 26 mA into the ZGS.

The electrostatic quadrupoles have 4" apertures and operate at voltages up to 40 kV, positive and negative relative to ground. Once they have been voltage-conditioned, which usually takes only a few minutes following a vacuum system pump-down, no voltage holding difficulty is experienced with them at top voltages. A Sorensen regulator is used to stabilize the ac input voltage to the power supplies. A separate positive and negative supply with common ac control is used on each quadrupole in the first set; the first and third members of the second set are fed from the same supplies. A 10 MΩ resistor decouples each supply from the quadrupole and a

.002 μF capacitor across the input to the quadrupole maintains nearly constant voltage on the electrodes despite some ion collection during a beam pulse due to gas ionization by the beam.

As a note of interest, the high voltage bushings leading through the vacuum wall to the quadrupoles were made of Teflon. Two of these bushings evidently developed a corona condition between the central conductor and the surrounding Teflon, presumably due to only partial evacuation. This resulted in eventual puncture of the dielectric and arcing along its surface (in vacuum) to ground. The consequent decomposition of the Teflon caused contamination of the accelerating tube to the extent that operation became impossible.

Future Plans

As noted earlier, the accelerating tube is bonded together with epoxy, some of which is exposed to the vacuum regions, and constitutes an undesirable source of contamination of the high voltage surfaces. Furthermore, a small leak through one of the bonds has resisted our efforts to seal it completely vacuum tight. Any leakage from the pressurized region into the vacuum region, even though it may be only N_2, cannot be expected to improve the performance of the accelerating tube.

We are now in the process of assembling a new accelerating tube, using ceramic section to which copper flanges have been metallurigically bonded. The assembly will be made by welding these flanges together. Thus, no organic materials will be present in these seals. This should result in a much cleaner assembly; improved performance is anticipated.

The shields for the ceramic will be of different design in order to provide more effective shielding and also to reduce the voltage between any two adjacent electrodes, except in the accelerating gap. The latter will be remotely adjustable without breaking vacuum. This assembly should be ready for testing within about two months.

Because of the need for a large value protective resistor between the power supply and the high gradient column, and the consequent need for a fast voltage regulator to stabilize the column voltage during beam pulses, we are giving consideration to the development of a series regulator tube which would parallel the limiting resisor and would receive its operating voltage (of the order of 25 kV) from the IR-drop across the resistor during a beam pulse. Its beam would be keyed off at other times. The design being considered would be much like that of the high gradient accelerating tube, including a pressure vessel, but of smaller diameter and mass. It would have to withstand the full power supply voltage in the event of full breakdown across the accelerating column. Consequently, it would be designed to withstand 750 kV dc even though subject only to occasional pulses of that magnitude. It would operate in a closed loop mode by taking an error signal from the top of a compensated metering resistor with the electronics situated in the ion source terminal. One Klystron manufacturer has studied this suggestion and has prepared a proposal for detailed design and construction of an electron gun. The tube could be constructed from Klystron ceramic parts already designed.

Acknowledgments

Many individuals have made contributions to the design, assembly, and testing of the high gradient column. I wish to express particular appreciation for the efforts of J. Abraham, J. Madsen, and R. Stockley, and for the encouragement of Dr. R. L. Martin.

References

[1] R. Perry, et al, Argonne National Laboratory, Characteristics of Beam from the the Argonne ZGS Injector Linac, V International Conference on High Energy Accelerators, Frascati, Italy, September 9-16, 1965, Published in Proceedings of V International Conference on High Energy Accelerators, pp. 597-602.

[2] R. Dubois and J. Huguenin, "Measurements on a High Gradient Accelerating Tube Model - Investigations of the Properties of Titanium Electrodes," CERN 65-23 (June 10, 1965), European Organization for Nuclear Research, Geneva, Switzerland.

[3] M. E. Abdelaziz and R. Perry, Argonne National Laboratory, Beam Diagnostics of the 50 MeV Proton Linear Accelerator of the Argonne Zero Gradient Synchrotron, Proceedings of the 1968 Proton Linear Accelerator Conference Brookhaven National Laboratory, May 20-24, 1968, Published in BNL 50120 (C-54), vol. 1, pp. 198-202.

[4] C. D. Curtis, et al, "The Operation of the First Section of the NAL Linear Accelerator," NAL FN-201, National Accelerator Laboratory, Batavia, Illinois.

[5] E. Parker, "X-ray Emissions from the High Gradient Column," (September 18, 1970) Argonne National Laboratory, Accelerator Division, Argonne, Illinois.

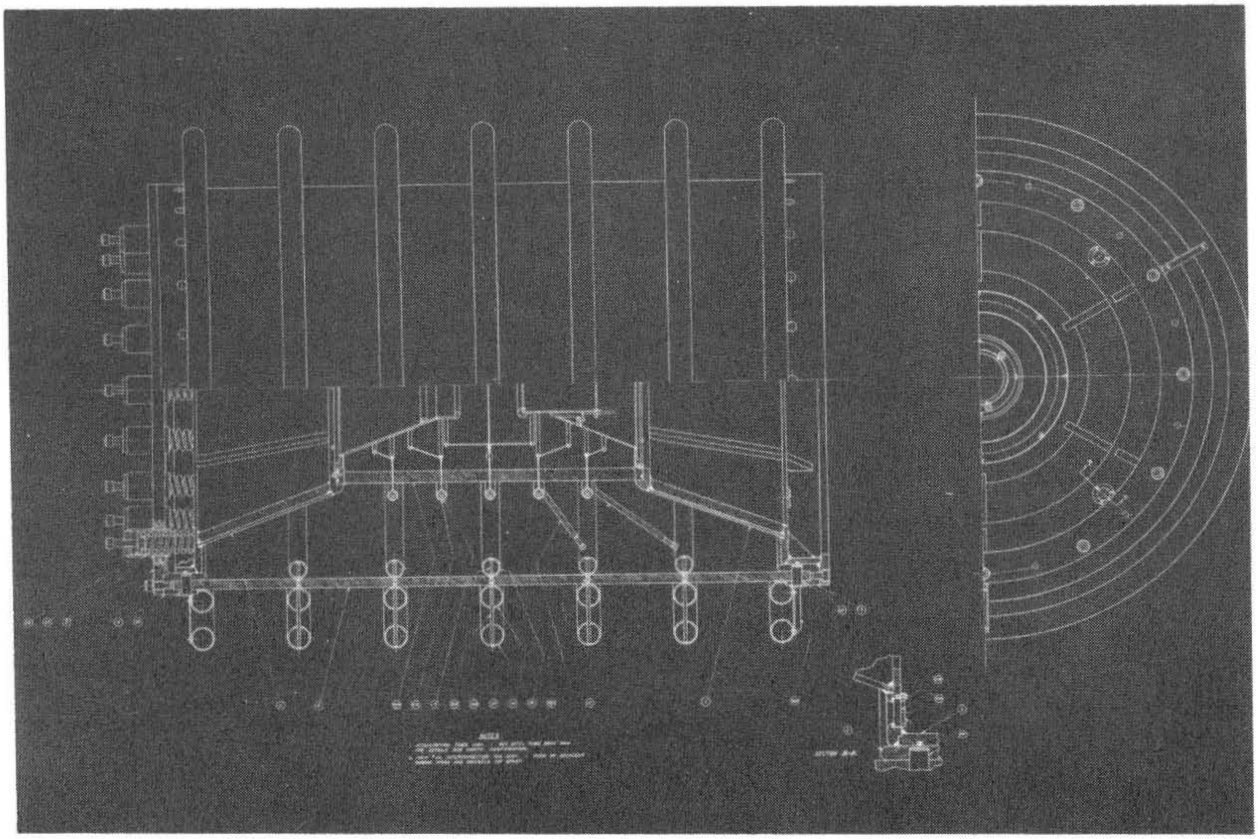


Fig. 1. Sectional view of 750-kV high gradient column assembly.

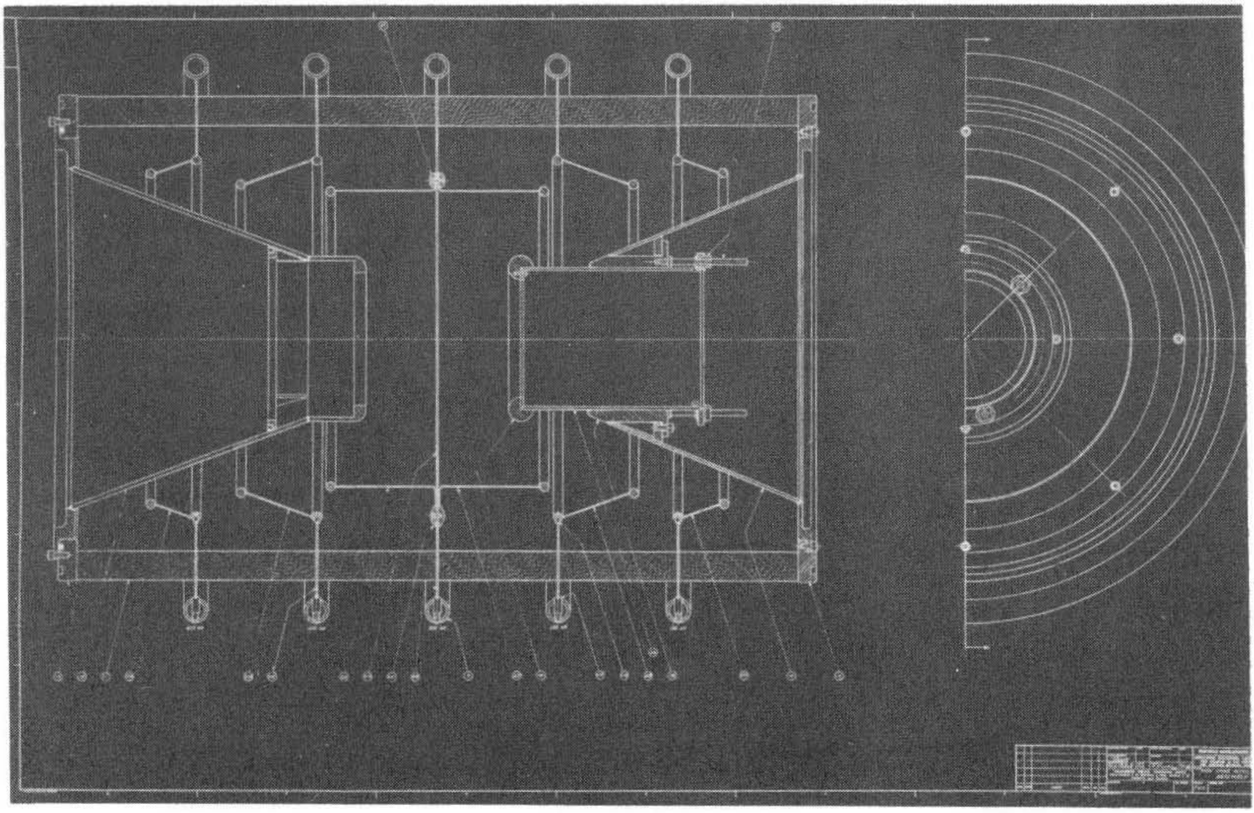


Fig. 2. Longitudinal section of high gradient accelerating tube.

Fig. 3. High gradient accelerating column subassemblies.

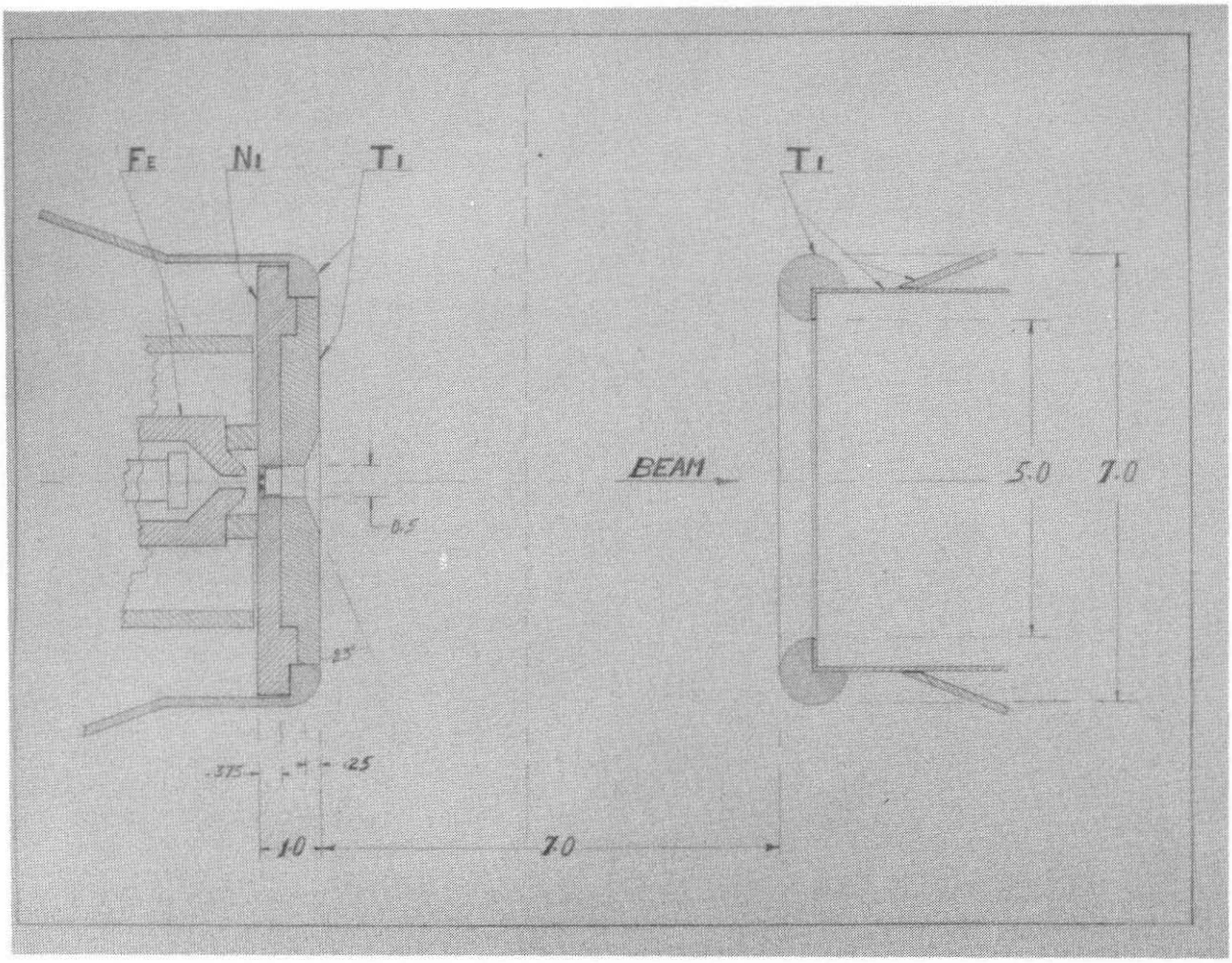


Fig. 4. Ion extraction and acceleration geometry.

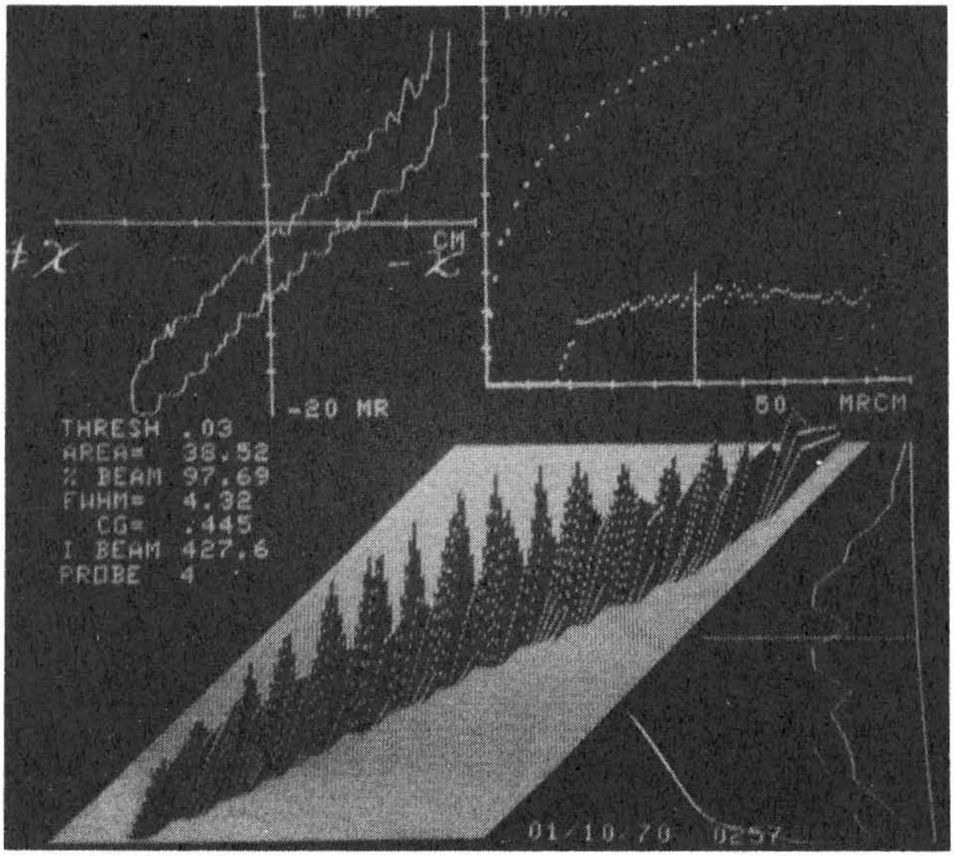
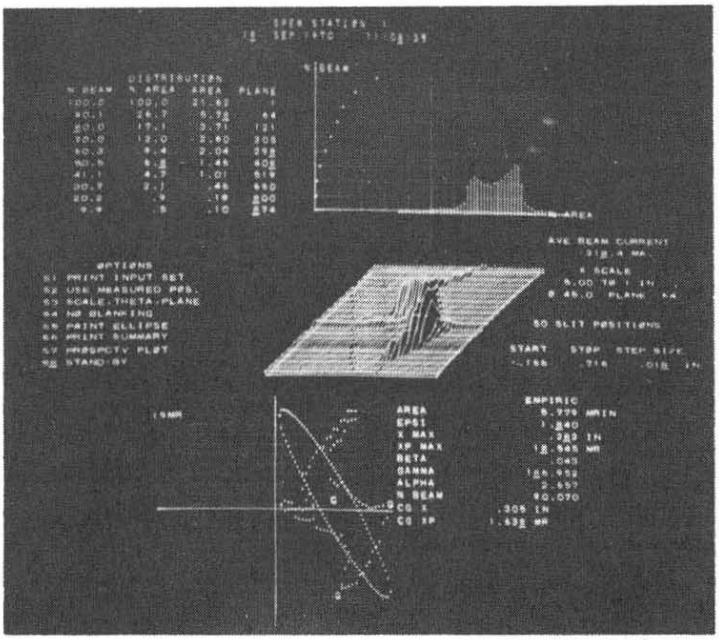


Fig. 5. Beam profile and beam-emittance figure for 750-kV, 270-mA beam from high gradient accelerating column using NAL system.



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  80.0    17.1   3.71    121
  70.0    12.0   2.60    205
  60.3     9.4   2.04    292
  50.5     6.8   1.46    408
  41.1     4.7   1.01    519
  30.7     2.1    .46    650
  20.2      .9    .19    800
   9.9      .5    .10    874

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55 PAINT ELLIPSE
56 PRINT SUMMARY
57 PRØSPCTV PLØT
58 STAND-BY

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Ø 45.0  PLANE 44

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EPSI        1.840
X MAX        .282 IN
XP MAX     12.545 MR
BETA         .043
GAMMA     124.952
ALPHA       2.657
% BEAM     90.070
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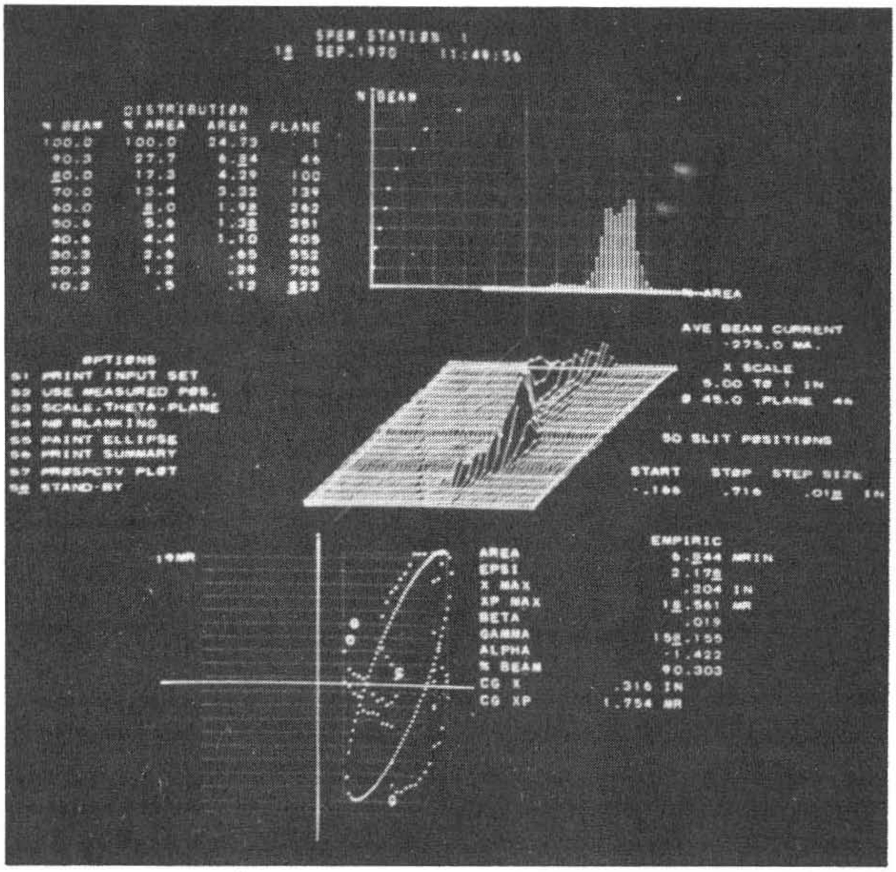
Fig. 6. Beam profile and beam-emittance figure for 750-kV, 218-mA beam from high gradient accelerating column using Argonne equipment with double modulator on ion source.



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  70.0    13.4   3.32    139
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  50.6     5.6   1.38    351
  40.6     4.4   1.10    405
  30.3     2.6    .65    552
  20.3     1.2    .29    706
  10.2      .5    .12    833

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Ø 45.0 .PLANE 46

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GAMMA     158.155
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% BEAM     90.303
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CG XP     1.754 MR
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Fig. 7. Beam profile and beam emittance figure for 750-kV, 275-mA beam from high gradient accelerating column using Argonne equipment with single modulator on ion source.