STATUS OF THE INTENSE NEUTRON GENERATOR STUDY PROGRAMME

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Introduction

This paper summarizes the status of AECL studies(1)(2) of the Intense Neutron Generator. ING is primarily a research instrument for the production of neutrons and mesons and is intended as the focal point of a many-sided research institute. A thermal neutron flux of 10^{16} n/cm^2.sec at the inner end of several beam tubes, high flux irradiation facilities, a saleable output of neutron produced isotopes, and a meson factory are highlights of this project.

The primary neutron source, $\sim 10^{19}$/sec, would be generated by bombarding a lead-bismuth target with a continuous 65 mA beam of 1 GeV protons.

The Project

Fig. 1 is a perspective view of ING showing the long linear accelerator building and one version of a meson experimental facility and a thermal neutron facility. Fig. 2 is an elevation of a more recent version of the thermal neutron facility where the horizontal proton beam is bent down to enter the lead-bismuth target. The target is surrounded by heavy water moderator and thick iron shields. The experimentalists have 360° access to the outside of the shielding with this arrangement. Fig. 3 is a sketch of the lead-bismuth target and moderator system. Molten lead-bismuth alloy enters at the top and is distributed by a vaned head to flow in a film on the pipe wall and then to completely fill the target tube at a level corresponding to mid-height of the moderator tank. This arrangement requires no vacuum window. Some of the parameters of the reference design target are given in Table I.

Fig. 4 is a schematic plan of the currently proposed layout of the whole experimental area. The location of the thermal neutron target with its radial neutron beam tubes and a future alternative facility is shown. There will be 0.5 to 1 mA of beam available for use in the meson area. We plan simultaneous acceleration of H^+ and H^- beams in the accelerator(3). The H^- beam will be magnetically separated and stripped to provide the required proton beam in this area.

The Accelerator

A Separated-Orbit Cyclotron was seriously considered as the accelerator to produce the required 65 MW proton beam(1). However, we have now chosen for detailed study a linear machine, adapting the design of the Los Alamos Meson Physics Facility for 100% duty factor(2). Improved accelerating structures developed at Los Alamos(4) and advances in microwave generators(5) influenced this choice.

Table II summarizes the main parameters of our current reference design. The injection system uses a dc duoplasmatron ion-source delivering ~ 120 mA of positive ions, about 70% protons; the beam is accelerated to 0.75 MeV using Pierce geometry for the extraction and accelerating electrodes. With a double-drift harmonic buncher, we hope for 85% capture efficiency into the linac. Alvarez structures consisting of 9 tanks and operating at 268.3̇ MHz accelerate the beam to 106 MeV. The first tank will be a $2\beta\lambda$ design to ease quadrupole design problems, aggravated by the higher than usual frequency and the transverse space-charge defocussing forces. At 106 MeV, a transition is made to a coupled-cavity accelerator operating at 805 MHz consisting of 322 tanks driven in pairs by 0.5 MW rf generators.

Although our design resembles that of the Los Alamos Meson Physics Facility, there are important differences. We require high current (65 mA) operation at 100% duty factor. There is, correspondingly, much more emphasis on high efficiency rf power generators, and we use a lower accelerating gradient to reduce copper loss. With the high average beam current, we can afford to spill only a very small fraction of the beam to keep activation to a manageable level(8). The 100% duty factor presents us with more severe thermal problems in the ion source and accelerator structure.

Simultaneous acceleration of both H^+ and H^- beams requires an odd multiple for the ratio of frequencies of the Alvarez and coupled-cavity sections. We have chosen $268.\dot{3}$ MHz for the Alvarez section and 805 MHz for the coupled-cavity section as the most reasonable compromise.

Major problem areas in the ING project are

- Radiation damage in the walls of the lead-bismuth target tube (a reminder that all problems do not lie in the accelerator design)
- Reliability of operation, and
- Small beam spill.

Reliable operation requires essentially all the radio-frequency generators to function simultaneously most of the time. Even with reliable power-tubes of more than 10^4 hours life-expectancy there will be relatively frequent faults in the rf system. Fortunately it does appear feasible to operate the accelerator, with some control adjustments, with one missing rf generator above the 200 MeV point (or even down to the transition if 0.25 MW units are used from 106 to 200 MeV), although it is not clear if operation can survive the transient conditions during a failure.

Beam spill in excess of a few microamperes will cause high activation levels in the accelerator structure requiring remote handling techniques for maintenance and would certainly be expensive to deal with.

The Study Programme

The three major programme items of our study are

- the 0.5 MW lead-bismuth loop
- the Proton Injection Experiment
- the Electron Test Accelerator

The lead-bismuth loop is our first attempt, on a reasonable scale, to acquire knowledge of lead-bismuth technology. Its size can be judged from the ½ MW rating of the heating section of this loop. Construction should be completed early in 1969.

We propose to construct an experimental injection system and first Alvarez tank, to accelerate a 65 mA beam. This experiment will test the ING accelerator design at full current to 5 MeV. We feel such an experiment is necessary; the space charge forces resulting from the high beam current make design calculations difficult and approximate. The experiment will permit performance tests under full current conditions of the ion source, accelerating column, low energy beam transport system, buncher, $2\beta\lambda$ tank, vacuum system and control of the integrated system. This experiment should result in an interesting and powerful accelerator with other potential uses and its design and construction will certainly give us a taste of the real problems of accelerator design.

Ion source development is making good progress. Fig. 5 shows part of the 150 kV ion-source test-stand dominated by the large getter ion pumps. Beam currents of ~ 100 mA, we hope with good emittance characteristics, have been extracted for several hours from a Duoplasmatron*. Filament lifetime equivalent to 11 days ING operation has been demonstrated. We are acquiring equipment for emittance measurements and other work has started on accelerator column design and beam analysis.

We also propose to construct a short prototype section of the main coupled-cavity accelerator as an engineering and systems test. The section

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*The design of this ion-source was developed from the designs of G.G. Kelley at ORNL.

will be loaded with a 65 mA electron beam, accelerating it to 7 MeV. A pre-accelerator section, followed by two tanks driven by 500 kW of rf power, will be assembled in a full size mock-up of the linac tunnel. The strongest justification for this experiment is that it forces us to give detailed consideration to all problems of the tunnel and systems design. We hope to find most of our mistakes in this short section rather than have to modify ~ 160 sections along a mile of tunnel.

We are studying Alvarez structures and coupled-cavity structures, both on paper and by measurements on models. A computer programme for field calculations written by Osama Aboul-Atta compares favourably in accuracy with the LALA Code developed at Los Alamos but it is several times faster; it is written in our APEX Code which is translatable into FORTRAN. We are at the beginning of studies of field stabilization against beam loading and error effects in Alvarez structures.

We are building a number of structures for high power tests at 100% duty factor.

Model 1 is an 805 MHz tank ($\beta = 1$) with 8 segments copied from the LASL EPA design. Assembly is well along. Fig. 6 shows the state of construction in March. We hope high power tests will start during July.

Model 2 is a $\beta = 0.65$ tank with 26 segments. Machining of components is in progress and the present schedule predicts high power testing toward the end of the year.

Model 3 is a 20 segment $\beta = 1$ tank which we hope will be the first tank for use in the Electron Test Accelerator experiment mentioned earlier. We are just acquiring copper for this tank.

A 4 ft. long model Alvarez Tank is being built for high power tests. The outer tank is now being made and design of the cooling, end-plates and drift tubes is nearly complete. Fig. 7 is a sketch of the cross-section of this tank indicating the design concept. The tank is split horizontally for access to the drift-tubes; a flange-weld will make the vacuum seal. The weld can be ground off to open the tank and then re-welded for re-assembly. We hope for high power tests starting about the end of the year.

Development of radio-frequency power generators will be discussed in a subsequent paper by P.J. Waterton. We have a 100 kW cw Amplitron test set and have successfully operated an Amplitron near this level with a clean spectrum. Corresponding tests of a 500 kW Amplitron should start in the early summer. Tests of a 100 kW klystron are also expected to start in June. Tests of a 1.2 MW 268.3 MHz triode amplifier are planned for early summer.

We chose crossed-field devices for our initial studies because they have demonstrated 85% dc - rf conversion efficiency(9). The high efficiency is very desirable for our project but must be balanced against the low gain and transparency to reflected power of Amplitron-like devices, which cause complications in system design. Klystrons have recently been demonstrated with efficiencies above 50% and if the trend continues, they will become a serious contender for our application.

Because of our demanding requirements on rf power sources, we have begun an in-house programme in tube design to acquire a good understanding of factors affecting performance.

So far we have made only a limited assessment of control problems associated with beam spill and of some ideas on how to deal with them. Regulation problems primarily arise in control of the phase and amplitude of the accelerator fields. Fig. 8 shows an example of the calculated loss from phase stability in the coupled-cavity section. In this case fields were assumed to have a random error distribution with standard deviations of ± 1% in amplitude and ± 1° in phase in both the Alvarez and coupled-cavity sections. Loss from stability exceeds the permissible radial spill indicated by the dotted line by an order of magnitude even when the stable phase angle was adjusted from tank-to-tank in an attempt to minimize the loss*. A proposal to use a doublet

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*Constant total copper-loss was used as a criterion in adjusting phases.

quadrupole focussing system is being examined to see if we can transport most of the lost particles to the end of the machine where they can be dumped by the first bending magnet.

It has been suggested that error signals might be derived by sensing beam behaviour rather than by using the more conventional standard reference signals. In any case, the latter would be needed to tune the machine before beam injection begins and the value of beam behaviour in error control remains an open question.

Conclusion

In the next twelve months we hope to have satisfied ourselves about feasibility issues and to have had experience with all major components. Beyond this we will be relying on the two major experiments mentioned earlier - the Proton Injection Experiment and the Electron Test Accelerator.

We are still working towards project approval. Last year the Science Council of Canada studied our proposals and their Study Reports prepared in December, 1967 have been issued(10)(11).

The Council recommended approval in principle to the Government in March, 1967 and funding (7.5 million dollars) for development of a "demonstrably feasible design with firm cost estimates". We currently have about 30 professional staff together with 10 attached engineers working on the study.

Acknowledgements

The considerable help of the Medium-Energy Physics Division staff at the Los Alamos Scientific Laboratory is difficult to acknowledge satisfactorily. Their patient advice and encouragement and their LAMPF design concept have been an important foundation for our work.

The ion source and injection studies at CRNL are the work of J.H. Ormrod and his collaborators; H.R. Schneider has been leading the accelerator structures studies and J.G. Bayly the control and instrumentation studies. The rf sources and magnet study programmes are credited in later papers. Many others have contributed.

References

(1) The AECL Study for an Intense Neutron Generator (Technical Details) ed. G.A. Bartholomew and P.R. Tunnicliffe. AECL Publication 2600 (July 1966).

(2) ING Status Report, July 1967. ed. T.G. Church. AECL Publication 2750.

(3) A Variant for ING Beam Splitting Using H^- Ions. C.H. Westcott, AECL unpublished report FSD/ING-76 (Dec. 1966).

(4) Resonantly Coupled Accelerating Structures for High-Current Proton Linacs. B.C. Knapp et al. I.E.E.E. Trans. on Nucl. Sci. NS-12 159 (1965).

(5) The Super-Power Amplitron. J.F. Skowron, W.C. Brown & G.W. McMaster. Microwave J. Oct. 1954.

(6) ING Accelerator 2nd Reference Design, Part A. Design of a 268.33 MHz Alvarez Linac. B.G. Chidley. AECL unpublished report FSD/ING-90A (May 1967).

(7) ING Accelerator 2nd Reference Design, Part B. Design of an 805 MHz Coupled-Cavity Linac. B.G. Chidley. AECL unpublished report FSD/ING-90B (May 1968).

(8) Radiation Levels from Beam Spill in ING. I.M. Thorson. AECL unpublished report FSD/ING-89 (April 1967).

(9) Twenty-Kilowatt 890 Mc/s Continuous-Wave Magnetron. J.R.J. Twisleton. Proc. I.E.E. 111, 51 (1964).

(10) The Proposal for an Intense Neutron Generator; Initial Assessment & Recommendations. Science Council of Canada. Report No. 2 (Dec. 1967) The Queen's Printer, Ottawa.

(11) The Proposal for an Intense Neutron Generator; Scientific & Economic Evaluation. Science Secretariat. Special Study No. 4 (Dec. 1967). The Queen's Printer, Ottawa.

DISCUSSION

(P. R. Tunnicliffe)

BLEWETT, BNL: Is the 1.2 MW triode commercially available?

TUNNICLIFFE, AECL: The tube we are using is an RCA A15039. I believe the tube has never been run at more than 750 kW. The estimated maximum rating, if we can achieve 60% efficiency, is about 1.5 MW rf output.

CHRISTOFILOS, LRL: How large is the physics and engineering staff in this development?

TUNNICLIFFE, AECL: We have about 40 professionals. They are about equally divided between physicists and engineers.

KUNTZ, KARLSRUHE: I would like to ask in regard to the electron test experiment: will you operate with a continuous beam or have you a chopping device?

TUNNICLIFFE, AECL: With a continuous beam, in the sense that there is 100% duty factor.

MUELLER, LASL: Could you say what emittance you are asking for at the entrance to the linac?

ORMROD, AECL: 0.1π cm-mrad normalized.

WARNER, CERN: Were cavity calculations done on LASL type (805 MHz) cavities or Alvarez-type cavities?

TUNNICLIFFE, AECL: They were on the LASL type cavities. Lee-Whiting has a paper in the proceedings on Alvarez structures.

LEE-WHITING, AECL: A few calculations have been done on Alvarez structures and we are now trying to do the calculations for the 2 $\beta\lambda$ cells in the first tank.

TABLE I

Thermal-Neutron Target

Thermal Flux at Beam Tubes	10^{16} n/cm^2.sec
Source Strength	10^{19} n/sec
Target Material	Pb-Bi eutectic (44.5 wt% Pb)
Target Dimensions	20 cm diam x 60 cm effective length
Total Charge Pb-Bi	52 tonnes
Flow (flooded section)	6 m/sec (325°C. → 450°C.)
Moderator	D_2O
Moderator Tank	120 cm radius
Shield	Iron, heavy concrete
Shield Thickness (Midplane)	450 cm (iron)
Beam Power	65 MW
Target Power	38 MW
Moderator Power	16 MW
Shield Power	11 MW

TABLE II

Linear Accelerator Design Parameters(6) (7)

Output energy	1000 MeV
" " spread	∼ ± 3 MeV
Output current, positive ions	65 mA
Emittance-Invariant	∼ 10π mm. mr.
Output current, negative ions	∼ .75 mA
Length	1540 m.
Injection	
Positive ion source type	Duoplasmatron
current	120 mA (70% protons)
D.C. accelerating voltage	750 kV
Buncher (double-drift harmonic type)	27 kV fundamental 12 kV 2nd harmonic 0.98 metre drift space
Capture efficiency into linac	85%
Alvarez Section	
Injection energy	750 keV
Output energy	106 MeV
Operating frequency	$268.\dot{3}$ MHz
Length	110 metres
Input admittance invariant	7.6π mm. mrad.
Input energy spread	± 15 keV max.
Number of tanks	9
Tank 1	$2\beta\lambda$ design, length 6 metres Energy gain 4 MeV Quadrupole magnets in every drift tube, gradients 5 to 2 kg/cm, $\cos\varphi_s = 0.82$
Tanks 2-9	$\beta\lambda$ design, length ∼ 12 metres Quadrupole magnets in alternate drift tubes, gradients 4 to 2 kg/cm in tank 2, others 1 kg/cm, $\cos\varphi_s = 0.9$

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TABLE II (continued)

Alvarez Section (continued)

Tank diameter	~ 70 cms.
Drift tube diameter	~ 12 cms.
Drift tube bore	1.5 to 3.0 cms.
Tank separation ($2\beta\lambda$)	22 to 82 cms.
R.F. power requirements (approx.) (beam + loss)	0.4 MW tank 1 1.2 MW tanks 2-9
R.F. generators	1.2 MW/unit (one/tank) (tank 1 - special)
Total R.F. power	10.0 MW
Total R.F. losses	3.5 MW

Coupled-Cavity Section

Injection energy	106 MeV
Output energy	1000 MeV
Operating frequency	805 MHz
Length	1430 metres
Number of tanks	322
Average energy gain/tank	2.8 MeV
tank length	3.4 metres
tank diameter	28 cms.
beam hole diameter	3.8 cms.
power/tank	0.25 MW
$\cos\varphi_s$	0.9
Tank spacing	~ 1 metre
Focussing	1 quadrupole doublet/tank interspace to 216 MeV, gradients 2.5 to 3.2 kg/cm followed by singlets/tank interface to 1000 MeV, gradients 0.45 to 0.9 kg/cm.
R.F. generators	0.5 MW (one/2 tanks)
Total R.F. power	80.5 MW
Total R.F. losses	22.4 MW

Shielding & Activation

Proton Energy MeV	Maximum beam spill allowing reasonable access 10 hours after shutdown	Shielding thickness metres of sand
10	500 nA/metre	2.3
50	50	5.0
200	10	7.6
1000	2	8.0

R.F. Power Supplies

Main power amplifiers	Crossed-field reentrant-beam devices (e.g. Amplitrons)
Driver amplifiers	Klystrons
D.C. power supplies	18 MW modules
Objective A.C. to R.F. conversion efficiency	80%

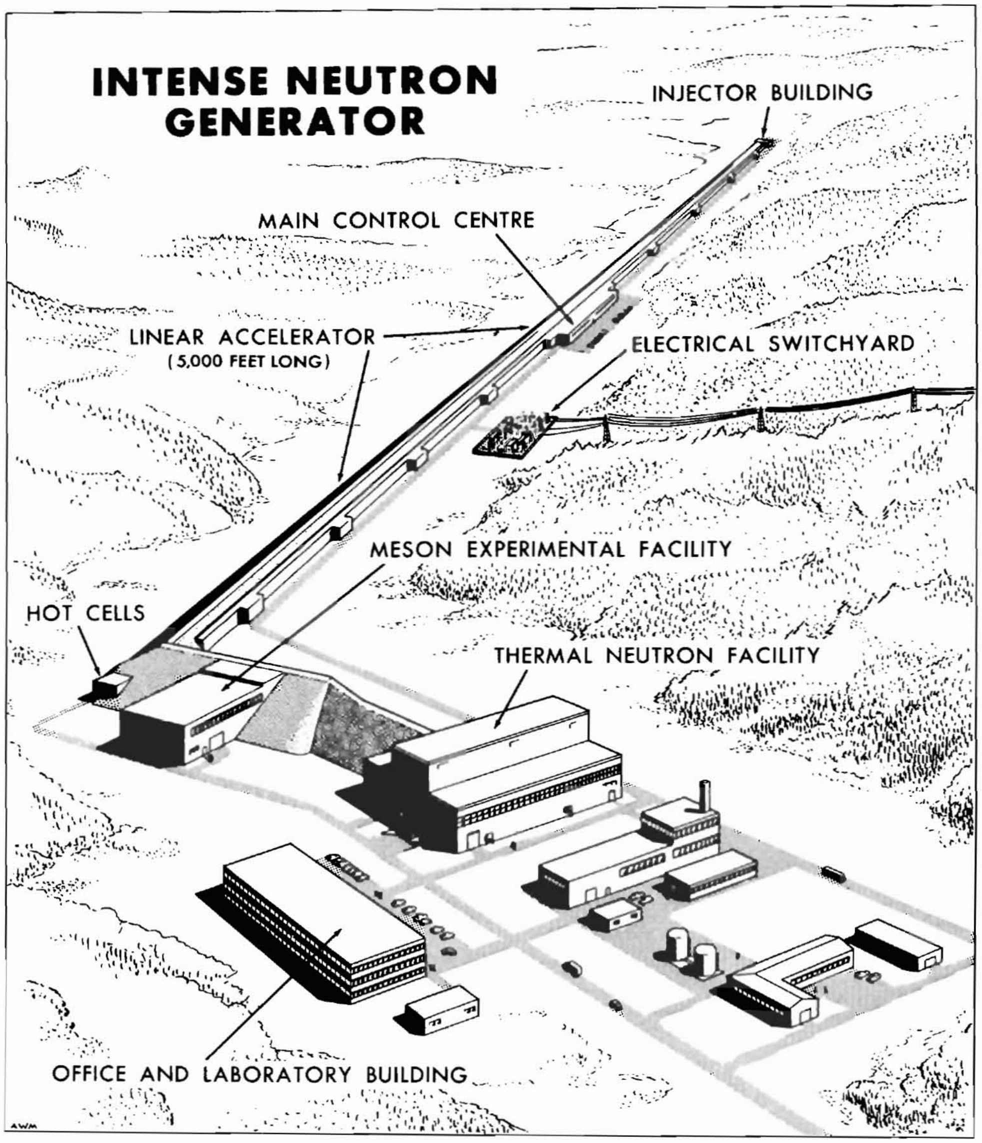

Fig. 1 Artist's Perspective of the ING Project.

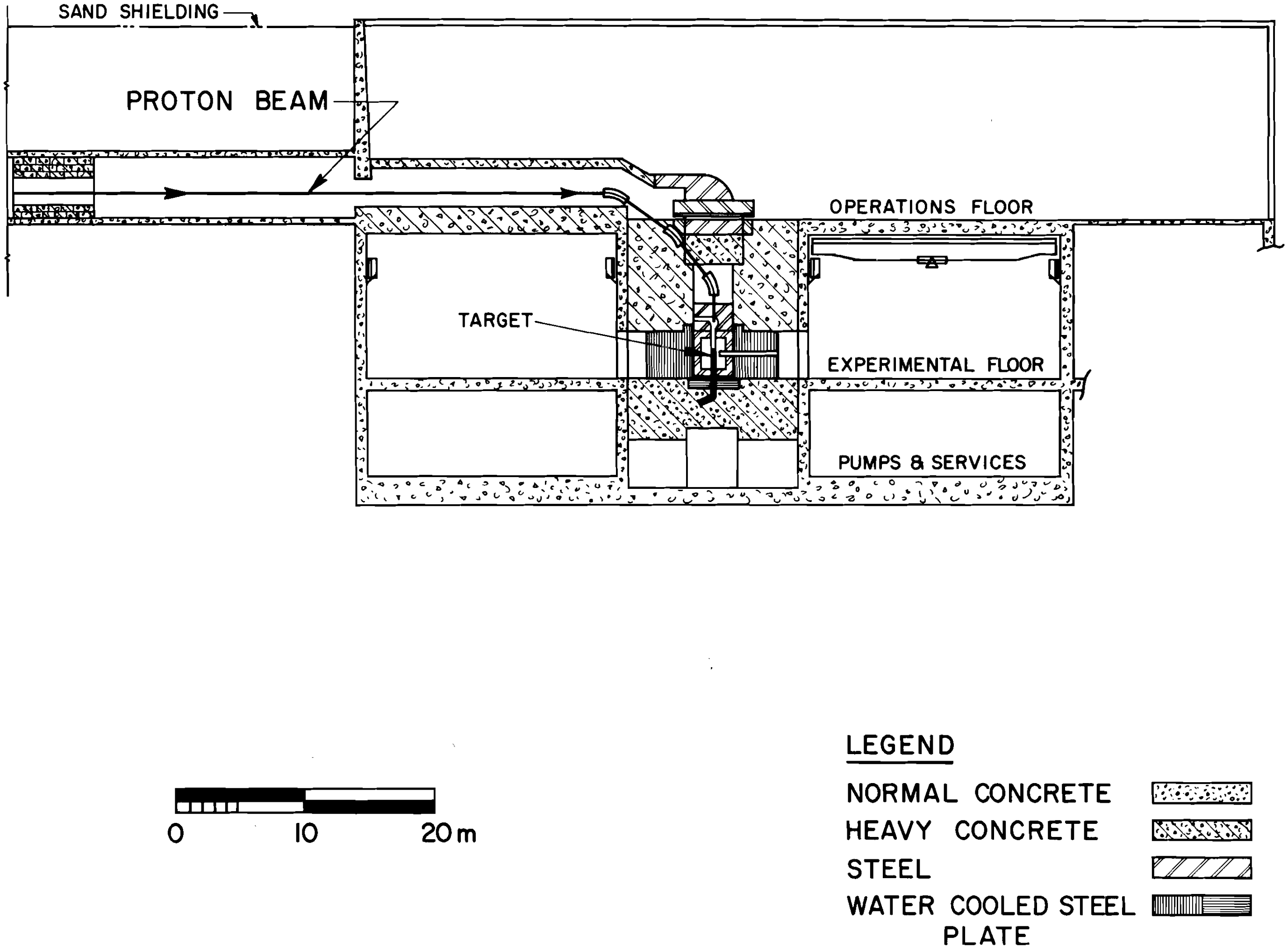

Fig. 2 The Thermal-Neutron Facility.

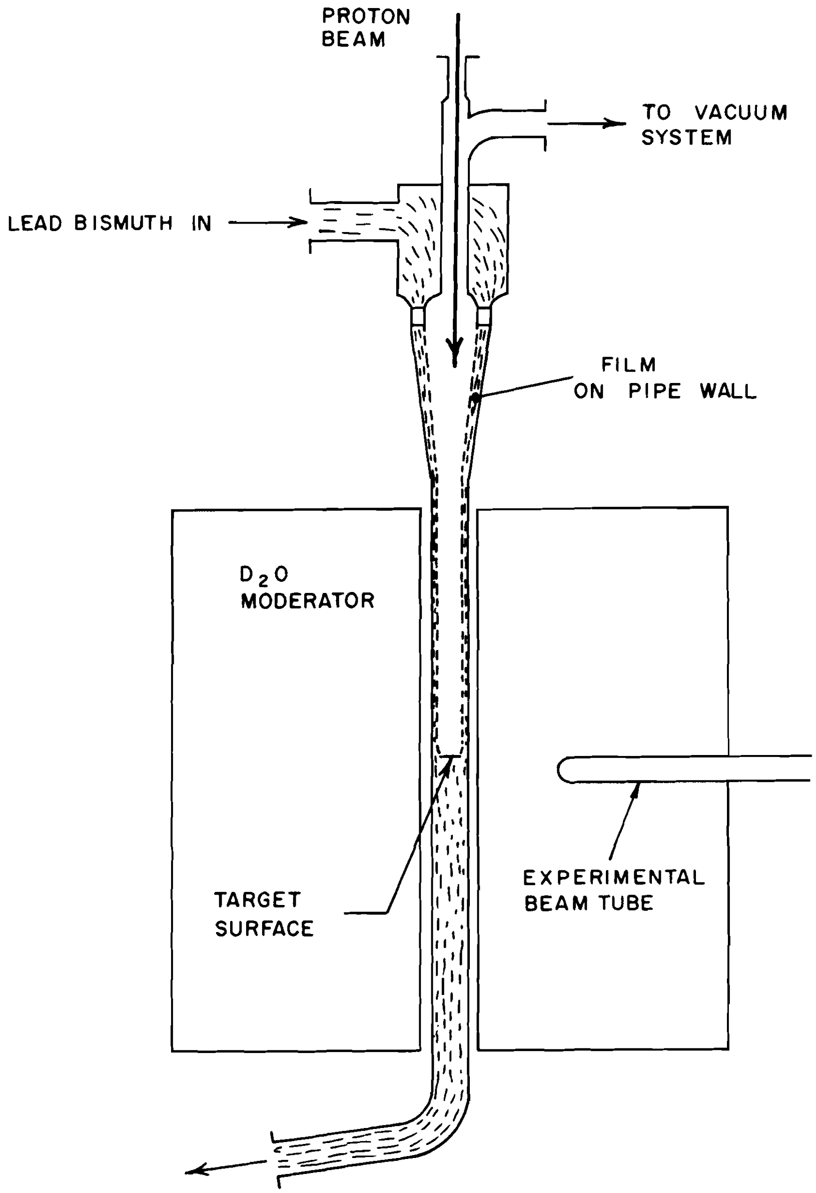

Fig. 3 The Pb-Bi Liquid-Metal Target.

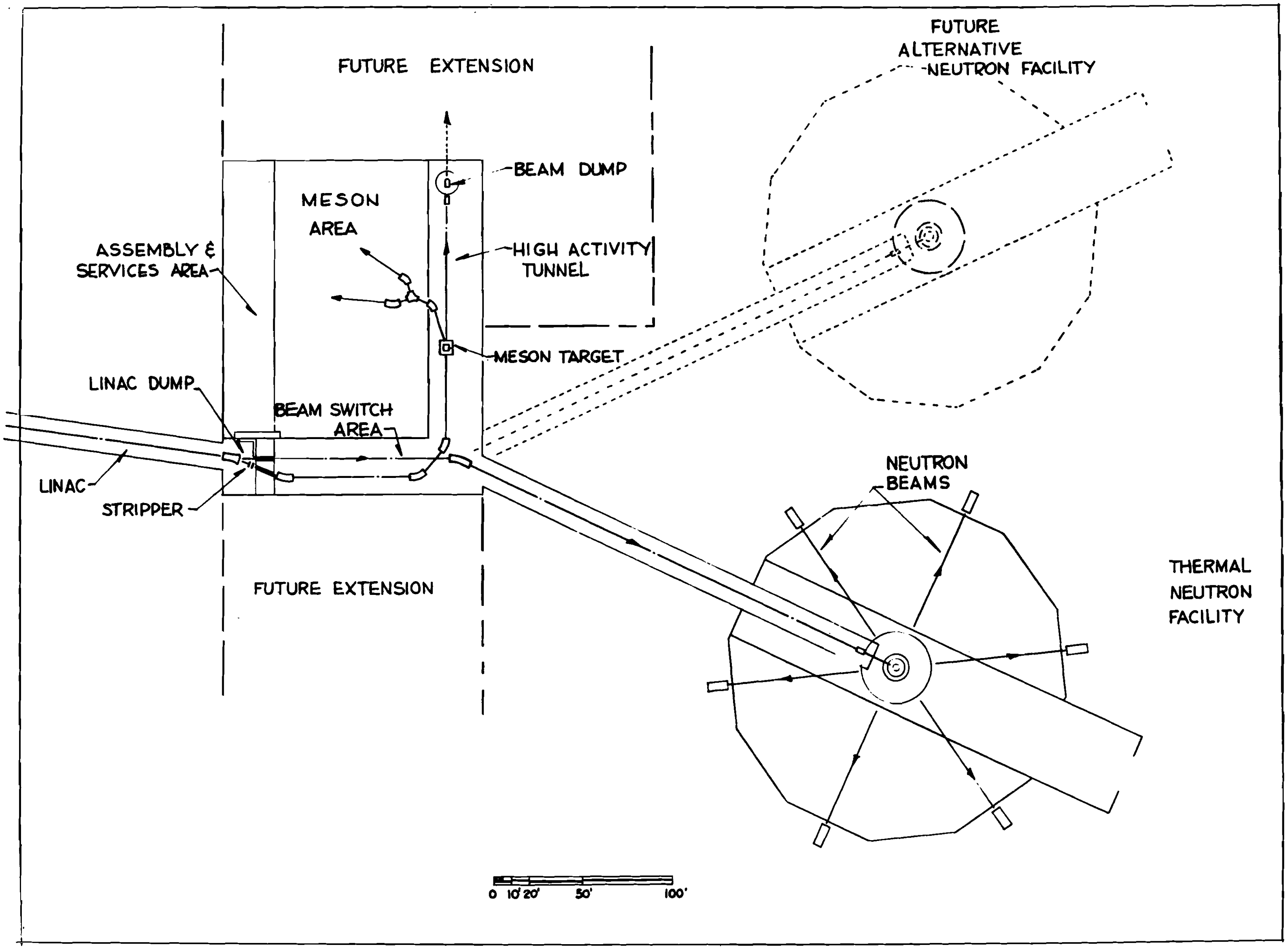

Fig. 4 Schematic Plan of the Experimental Areas.

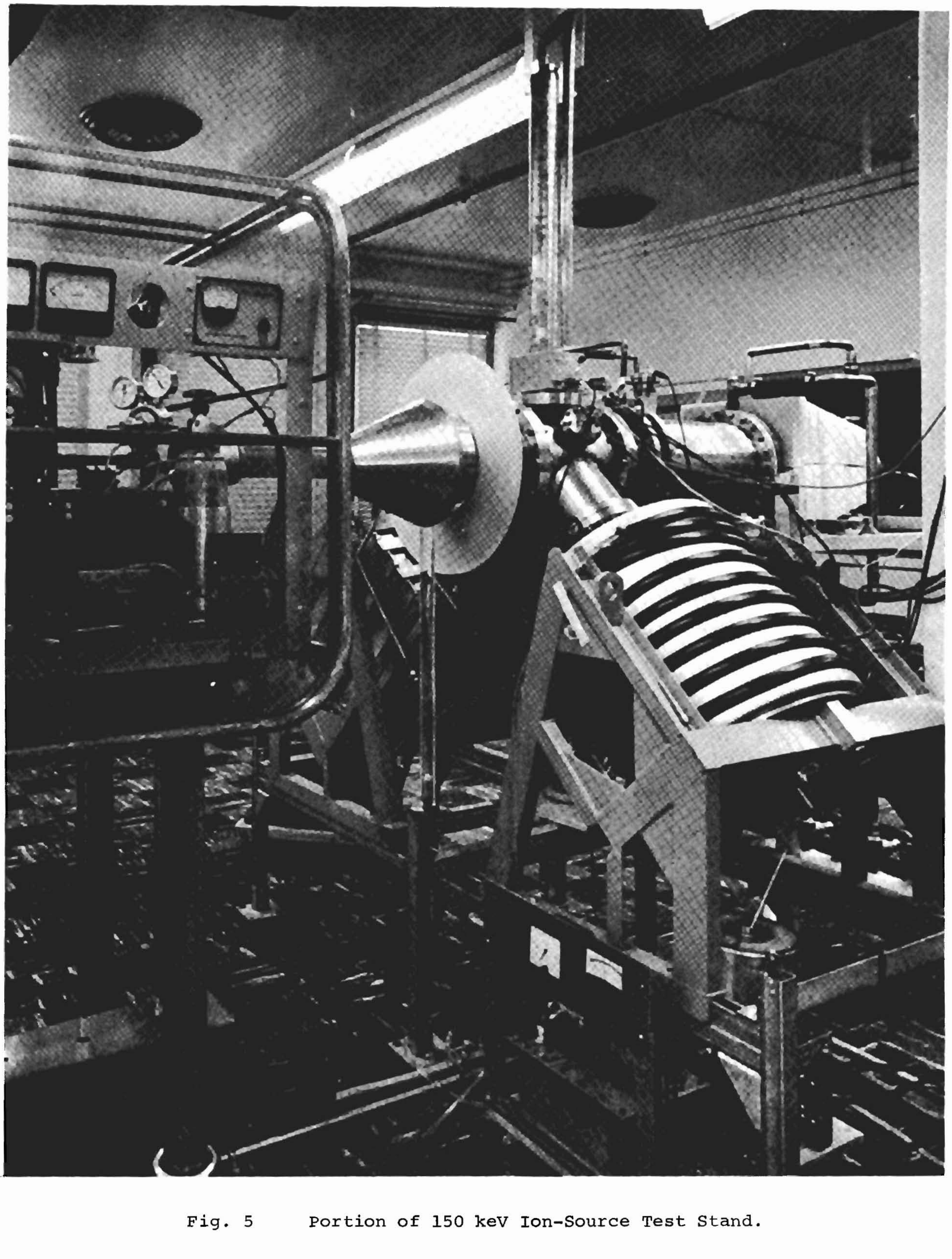

Fig. 5   Portion of 150 keV Ion-Source Test Stand.

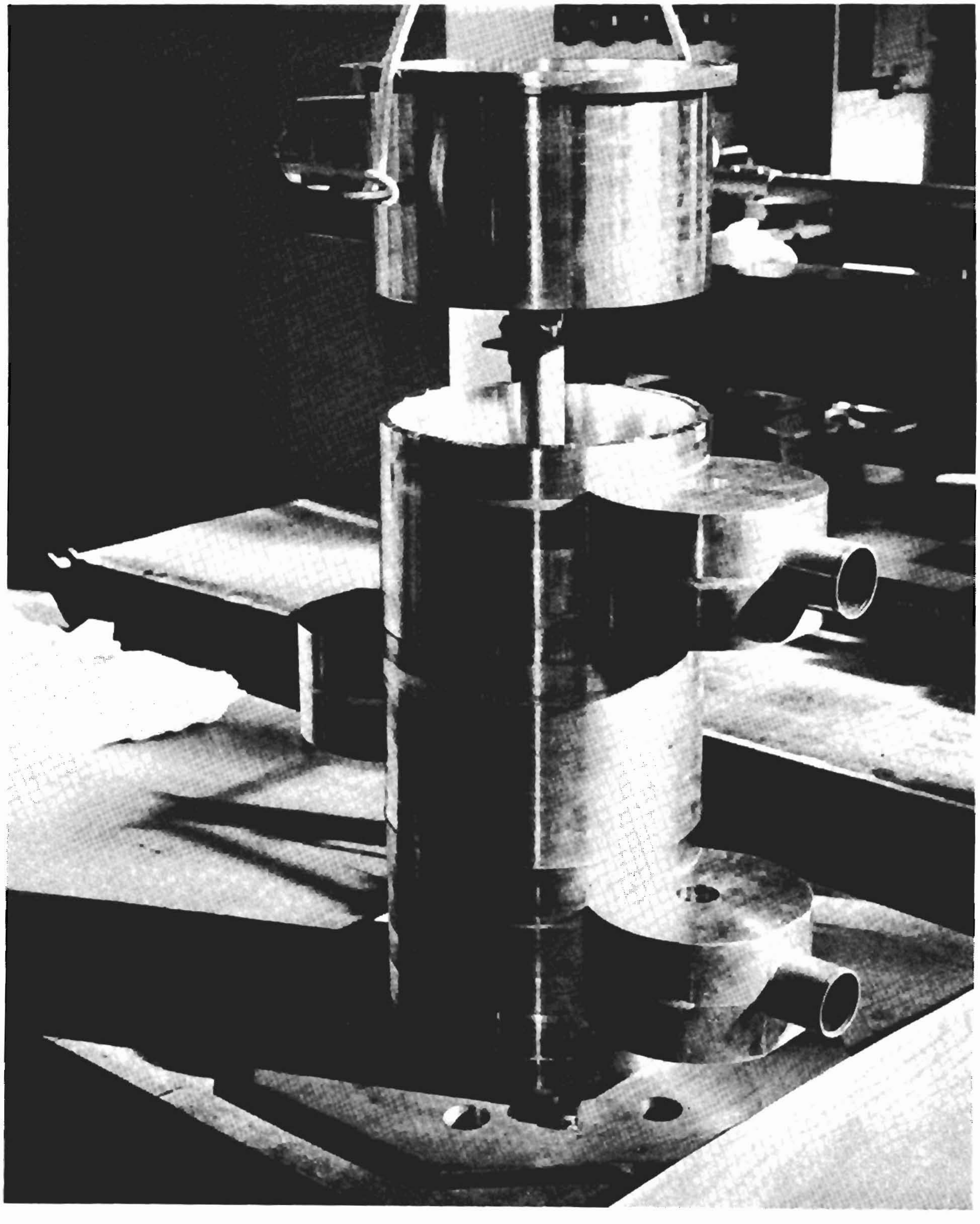

Fig. 6 Part of Model 1 Coupled-Cavity Tank in Assembly for Final Braze (March 1968).

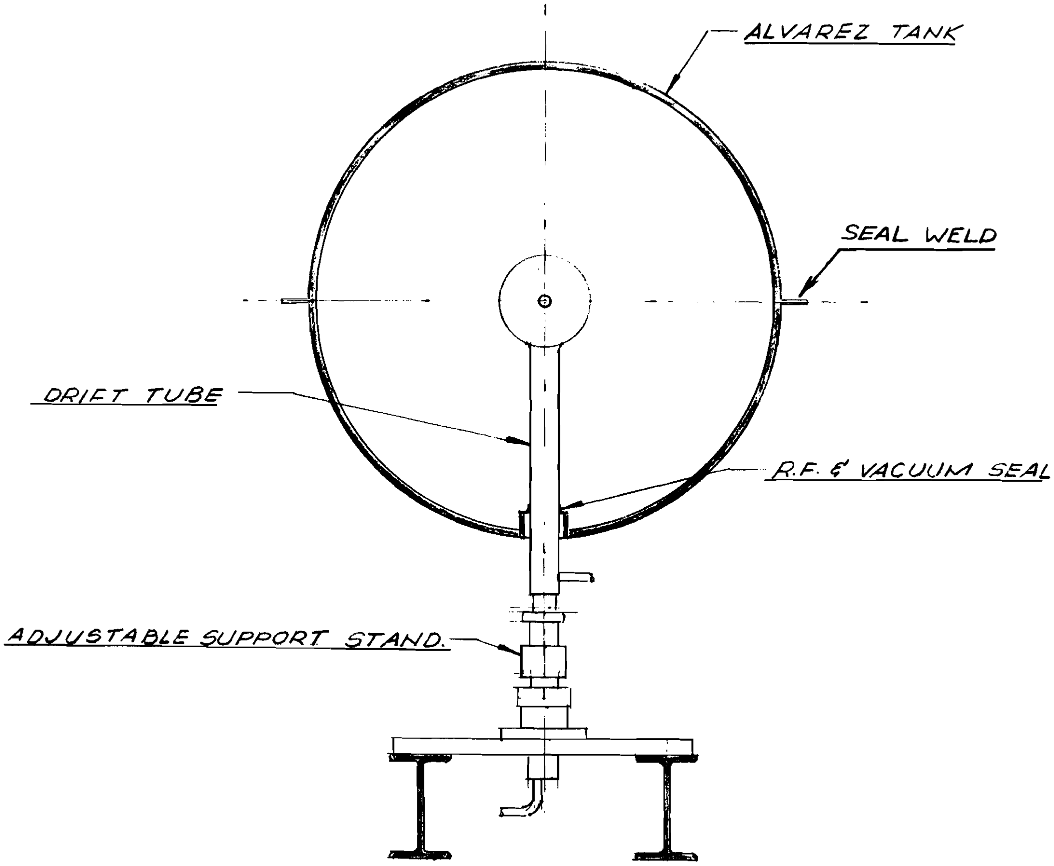

Fig. 7 4' Alvarez Tank Section.

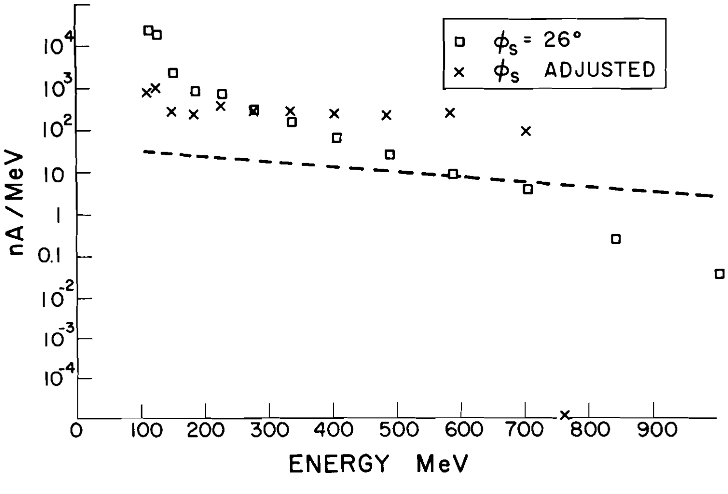

Fig. 8 Proton Loss from Phase Stability for 1% & 1° RF Errors (the slashed line is the estimated tolerable radial spill).