Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

RESEARCH POSSIBILITIES WITH AN INTENSE NEUTRON GENERATOR

Invited Paper

G. A. Bartholomew
Neutron Physics Branch, Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada.

As the title suggests this paper will depart somewhat from the general topic of this session and will be concerned more with applications of accelerators than with accelerators themselves. The particular application of interest at our laboratory concerns the use of a high current intermediate energy proton accelerator as the basis for a versatile intense neutron source. Chalk River's entry into the intermediate energy accelerator field with neutron production as the primary motivation is somewhat unusual. Although neutron production is also being explored by other laboratories interested in intermediate energy accelerators, e.g., Oak Ridge National Laboratory and Los Alamos Scientific Laboratory, it has not been the major motivation. Our initial motivation was in fact the production of thermal neutrons and this interest has remained foremost in our ING program[1,2]. We are currently writing a proposal for this project. Our target is to have a proton beam in 1973.

Figure 1 shows the presently conceived layout of the ING facility as it will look when fully developed. On the left is the proton accelerator shown here as a three-stage SOC. We have other drawings in which the accelerator is shown as a CW Linac and, as of now, our Accelerator group are not sure which of the two holds the greater promise of filling our special needs for high efficiency in CW operation, reliability, and accessibility. But I shall have to forego the temptation of launching into that story if I am to stick to my subject of research possibilities. Let us assume that to the left in this figure we have an SOC operation at 50 MHz and providing CW protons at about 1 GeV with a beam current of about 65 mA. These figures are subject to revision as the overall design matures but we shall use these as nominal figures. The energy and current are not far from what will ultimately be required in any case. However, if we settle for a Linac the beam micropulse frequency will probably be closer to 200 MHz.

The beam transport and experimental area layout following the accelerator are designed with two objects in mind: 1, to provide proton beams of required characteristics feeding four distinct neutron producing target facilities and a meson factory, with a minimum of beam splitters and bending magnets; 2, to leave generous spaces between the various components to permit the inevitable modifications and additions, and to make room for ample shielding.

Now let us consider the various subunits. The main beam path, beam No. 1, leads to the thermal neutron target facility which I will discuss later. After emerging from the accelerator, beam No. 1 passes through a two-way splitter which ejects trains of micropulses (either singly or in groups) to two secondary transports. Beam No. 2 which has a current of about 1 mA will eventually strike a deuterium target for production of fast neutrons. Beyond that target the spent beam No. 2 will be deflected out of the way to an underground beam dump. Beam No. 3 which will be at most of the order of 1:5000 of the main beam i.e., $< 15\ \mu A$, will be split again with about $0.1\ \mu A$ going to an advanced power technology laboratory and the remainder to a resonance neutron target not unlike that used with the Nevis cyclotron.[3] The heavily shielded parts of the transport tunnels from beams No. 1 and 2 enclose meson targets from which meson channels can be led out to the meson experimental area. Nominal value for the proton beams delivered to the various neutron targets are listed in Table I.

A word should be said about beam splitters. We have not yet launched a splitter development program but have satisfied ourselves that a splitter system approaching our requirements is not out of the question, given time for development. Our cursory study has led us to believe that a parallel plate wave guide with an RF pulse travelling counter current to the beam would make a good micropulse deflector. This would be followed by a drift space with septum magnets. Generators delivering triggered 10-100 kV pulses with ~ 1 nanosecond rise times are already discussed in the literature.[4] A crucial requirement will be to find a way of driving such a device at a repetition rate up to 0.5 MHz in phase with the beam. It doesn't seem to be unduly optimistic to assume that an acceptable splitter can be built within our timescale.

Now let us turn to the targets and the neutron outputs to be achieved from each. The basis of the whole concept is the spallation reaction which is demonstrably more efficient than all other methods presently available as measured in terms of the neutrons emitted per unit of heat generated in the source itself. Now I shan't go into details of the neutron yields and heat liberated in spallation but I do want to say that this whole question is now very well understood thanks to recent calculations[5] and to direct yield measurements carried out a year ago on the Cosmotron by a joint team from Oak Ridge and Chalk River.[6] It should also be mentioned that the idea of using spallation to produce large sources of neutrons has already had a considerable history. It formed the basis for the MTA project[7] at Livermore prior to 1954. About that time Dr. Lewis at Chalk River also initiated a study of spallation[8,9] as an alternative to reactors as a source of neutrons to produce fissile material. Around 1963 when our present ING study got under way at Chalk River, Alex Zucker at Oak Ridge and P.A. Egelstaff and F.M. Russell at Harwell and the Rutherford Laboratory were also considering the potentialities of neutron sources of this type.[10,11]

Table II lists the principal parameters and dimensions of the ING thermal neutron source (target and moderator) as it is presently conceived. The beam tube flux of 10^{16} cm^{-2} sec^{-1} is the design objective. This flux will be generated at the inner- (source-) end of a beam tube. This adjective "perturbed" signifies that flux depression effects introduced by the beam tubes themselves are taken into account. The source strength for target and moderator of materials and dimensions shown is required to be 10^{19} n sec^{-1}. The proton beam required is 65 mA at 1 GeV i.e. a beam power of 65 MW. This power is spread between source, moderator, and shield in the proportion 39: 16: 10 MW. The details of number of beam tubes and irradiation facilities are given at the bottom. In many ways the experimental facilities resemble those of a compact-core high-flux research reactor such as HFBR.[12] Figure 2 presents a view of the target, moderator, and shield showing the positions of the various experimental facilities. The split cylinder surrounding the target tube is a beryllium neutron multiplier which increases the neutron yield by the Be^9(n,2n) reaction. You will notice that most of the beam tubes are tangential to the target, an arrangement which increases the thermal to epithermal flux ratio in the neutron beams. The beam tubes are 4 inches in diameter. All are provided with vertical access tubes which permit introduction of targets or moderators in the high flux region without interfering with the beam tube proper. When any tube, horizontal or vertical, is not in use it will be flooded with D_2O to reduce leakage of neutrons. The shield must be $\sim$ 15 feet of iron to screen out high energy neutrons. These are principally cascade neutrons in the range 15 MeV to 1 GeV which contribute some 20% to the total neutron output. Figure 3 shows the unmoderated neutron spectrum from the target. It consists of an evaporation spectrum peaked at $\sim$ 3 MeV reminiscent of a fission neutron spectrum, and a high energy cascade tail extending to 1 GeV. For most experiments these cascade neutrons are unlikely to contribute a serious background compared to that from incompletely moderated neutrons from the evaporation spectrum. The background from keV neutrons in this device should be similar to those from reactors which are known to be tolerable. However, the neutron beams, particularly because of this very high energy component, present health hazards much more severe than those from reactors. This may necessitate conducting the neutron beams in enclosed pipes to beam catchers outside the building as suggested in Figure 4. These beam pipes can be broken into, where required, to insert experimental equipment; their main purpose will be to prevent personnel from intercepting the beams. Figure 5 shows an elevation view of the target, moderator, and shield with the incoming proton beam tube directed at the target in a downward direction. The liquid metal heat exchanger system is situated below floor level.

I need spend little time describing the fast neutron and resonance neutron targets. Both are of conventional design and present few new problems. Time-of-flight systems require space for flight paths and we have made provision for these; some 1000 meters is allowed for in at least one direction from the resonance neutron target blockhouse, which, as you may recall in Figure 1, was situated at the end of beam No. 3. Provision will be

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

made for installing other shorter flight paths as required.

The three targets so far mentioned, for CW thermal neutrons, and pulsed resonance and fast neutrons, all provide exceptionally intense fluxes compared to existing facilities and we shall return to discuss these later. But next I would like to describe briefly the idea behind the fourth neutron facility which we call the advanced power technology facility. The central idea is to study, as a pilot plant, the effects of bombarding targets of U^{238} or thorium with 1 GeV protons. It is known from Monte Carlo calculations and direct measurements that the neutron yield per proton on a uranium target, for example, is about twice that for a lead-bismuth target because of contributions from fission.[5,6] But at the same time the heat in the target is about four times greater per proton than for lead-bismuth, again because of the excess heat contributed by fission. The latter property makes U^{238} or Th unsuitable as targets for the high thermal flux facility because, in that application, target heat is of critical concern and one must keep the target small to obtain high flux. However, if one's goal is to produce large numbers of neutrons instead of a high flux, targets of U^{238} and Th are favoured because it is possible, in principle, to use a large target and to spread the beam out to facilitate cooling. Such a target can be surrounded by a blanket of more fertile material to absorb neutrons. The whole assembly may be regarded as a facility for rapidly breeding fissile material without consuming U^{235}. One can conceive, in addition, of a cycle in which the heat from the breeder target and a reactor burning the fissile material is combined to drive a generator which supplies electrical power to run the accelerator and still has some left over for distribution.[13] Such systems are unlikely to become economically competitive until some time in the future and then only after a lot of development work. It is to study the basic physics and engineering of such systems that the advanced power technology target is included in the ING facility as a zero power device.

Now I would like to return to the neutron beam research facilities and summarize their capabilities in intensity, pulse characteristics and so forth. These are summarized in Table III.

The potentiality of these experimental facilities can be best illustrated with some comparisons with existing facilities. The thermal neutron facility has roughly the same number of beam tubes as HFBR but 13 times the nominal flux of that facility.[12] In addition the ING target will have a large capability for production of radioactive isotopes for research and industry, e.g. Co^{60}, and transuranic elements. Its beam tube flux is twice as great as the nominal flux in the HFIR reactor[14] flux trap and it will have more beam tubes. However, the isotope irradiation facilities in the ING thermal target will not be as extensive as those of HFIR. As a resonance neutron time-of-flight facility it will compare very favourably with all other systems including the latest generation of linacs, isochronous cyclotrons, and pulsed reactors. This sort of comparison is difficult to carry out in a fair way quantitatively since it depends on how the device will be used as well as on repetition rate, burst width, and peak neutron intensities in the burst[15] as well as on details of the geometry of target and moderator.[16] As a pulsed-fast neutron source in the energy range > 15 MeV the ING will be essentially identical to the Los Alamos Meson Facility.[17] It will also be comparable to LAMPF as a meson factory, but that is a little off my present topic.

Looking to future developments, one can foresee the possibility of coupling the accelerator to a storage ring which can be dumped periodically to greatly enhance the instantaneous pulse current delivered to any target. As an example, if one could store for 5 m sec and dump in 0.1 μ sec one would increase the instantaneous burst intensity in the thermal target by 5×10^4 i.e. 5×10^{23} n/sec in the peak at a repetition rate of 200 per second. The target would dissipate no more heat than in CW operation but certain changes would be required in design of the moderator assembly to make optimum use of the pulsed mode. Such a storage ring would require much development work and is not part of our immediate proposal for ING.

This neutron facility would, of course, have many applications, most of them springing quite naturally from existing experiments which need higher flux to accomplish work with higher resolution, greater sensitivity, or smaller samples.

 Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966

I don't want to present a long list of these applications, some of them are alluded to in the abstract or have been reported elsewhere[1], but what's more to the point, most of the experiments I could catalogue today may be passe by 1973 and a different set will be commanding our interest. I think it is clear that ING presents an unparalleled potential as a facility for neutron physics research and, once available, there would be no shortage of experiments that would take advantage of it.

References

1. G.A. Bartholomew, J.C.D. Milton and E.W. Vogt, "An Intense Neutron Generator Based on a Proton Accelerator", AECL 2059, 1964.

2. "The AECL Symposium on the Generation of Intense Neutron Fluxes", AECL 2177, 1965.

3. J. Rainwater, W.W. Havens, Jr., and J.B. Garg, Rev. Sci. Instr. 35, 263 (1964).

4. See for example D.F. McDonald, C.J. Benning, and S.J. Brient, Rev. Sci. Instr. 36, 504 (1965).

5. J.C.D. Milton and J.S. Fraser, "A Monte Carlo Calculation of Neutron Production in Heavy Element Targets by Protons in the Range 0.3 - 1 BeV", AECL 2259 (1964).

6. J.S. Fraser, R.E. Green, J.W. Hilborn and J.C.D. Milton, W.A. Gibson, E.E. Gross, and A. Zucker, Physics in Canada 21, No. 2, 17 (1965), to be published.

7. "Status of the MTA Process", LRL-102 (Dec) (1954).

8. W.B. Lewis, "The Significance of the Yield of Neutrons from Heavy Nuclei Excited at High Energies", AECL 968 (1952).

9. M. Bercovitch, H.H. Carmichael, G.C. Hanna, and E.P. Hincks, Phys. Rev. 119, 412 (1960).

10. A. Zucker, 1964, private communication.

11. F.M. Russell, 1963, private communication.

12. H. Kouts, Reactor Science and Technology Journal of Nuclear Energy, Parts A and B, 17, 153 (1963).

13. C.H. Millar, see ref. 2, paper No. 5.

14. T.E. Cole and A.M. Weinberg, An. Rev. Nuclear Sci. 12, 221 (1962).

15. G.A. Bartholomew, Proc. Int. Conf. on the Study of Nuclear Structure with Neutrons, Antwerp, 1965, North Holland in press.

16. R.G. Fluharty, Proc. Symp. on Pulsed High Intensity Fission Neutron Sources, Washington, 1965, CONF 650217, 11 (1965).

17. Proposal for a High-Flux Meson Facility at Los Alamos, New Mexico, Los Alamos Scientific Laboratory, 1964.

TABLE I

Characteristics of Proton Beams in ING

RF Frequency 50 MHz

Proton micropulse width $\tau \simeq 3$ n sec

Target	Beam	Beam Current	Proton Burst Frequency
Thermal	#1	$\sim$ 65 mA	50 MHz
Fast	#2	$\sim$ 1 mA	$\sim$ 0.8 MHz
Resonance	#3 a	$<$ 15 μA	$< 10^4$ Hz
NPT *	#3 b	$\sim$ 0.1 μA	$\sim$ 80 Hz

* Nuclear Power Technology

TABLE II

ING Thermal Neutron Facility

Beam Tube Maximum Flux (perturbed)	10^{16} n cm^{-2} sec^{-1}
Source Strength	10^{19} n sec^{-1}
Target Material	Pb-Bi eutectic, Zr tube, Nb liner
Target Dimensions	20 cm dia x 60 cm effective length
Moderator	D_2O
Moderator Thickness	100 cm
Shield	Iron, heavy concrete
Shield thickness at beam tube elevation	450 cm (iron)
Proton Beam	65 mA, 1 GeV, CW
Beam Power	65 MW
Target Heat	39 MW
Moderator Heat	16 MW
Shield Heat	10 MW
Facilities	5 tangential beam tubes 10 cm dia
	1 through beam tube 10 cm dia
	1 radial beam tube 10 cm dia
	7 vertical access tubes
	2 pneumatic rabbits
	5 vertical thimbles 15 cm dia
	18 hydraulic carriers
	1 cobalt blanket

TABLE III

Neutron Beam Characteristics

	Thermal Neutron Facility	Resonance Neutron Facility	Fast Neutron Facility
Flux or Burst Intensity	4 tangential tubes 10^{16} cm^{-2}sec^{-1} th 1 tangential tube 5×10^{15} " " " 1 through tube 10^{16} " " " 1 radial tube 10^{16} " " " rabbits 10^{16} " " " 2 vertical tubes 5×10^{15} " " " 3 vertical tubes 2×10^{15} " " " hydraulic carriers $\sim1\times10^{15}$ " " " Epithermal neutrons of various fluxes $\leq \sim 3\times10^{14}$ n cm^{-2} sec^{-1}	$\sim10^{11}$ n/burst $0 < E < 1$ GeV Pb target	$\sim 2\times10^{9}$ n/burst E = $\sim$ 1 GeV D_2 target
Rep.Rate sec^{-1}	CW	$\leq 10^{4}$ variable	$\leq 5\times10^{5}$ variable
Pulse Width n sec	--	≥ 3 unmoderated	~ 3

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

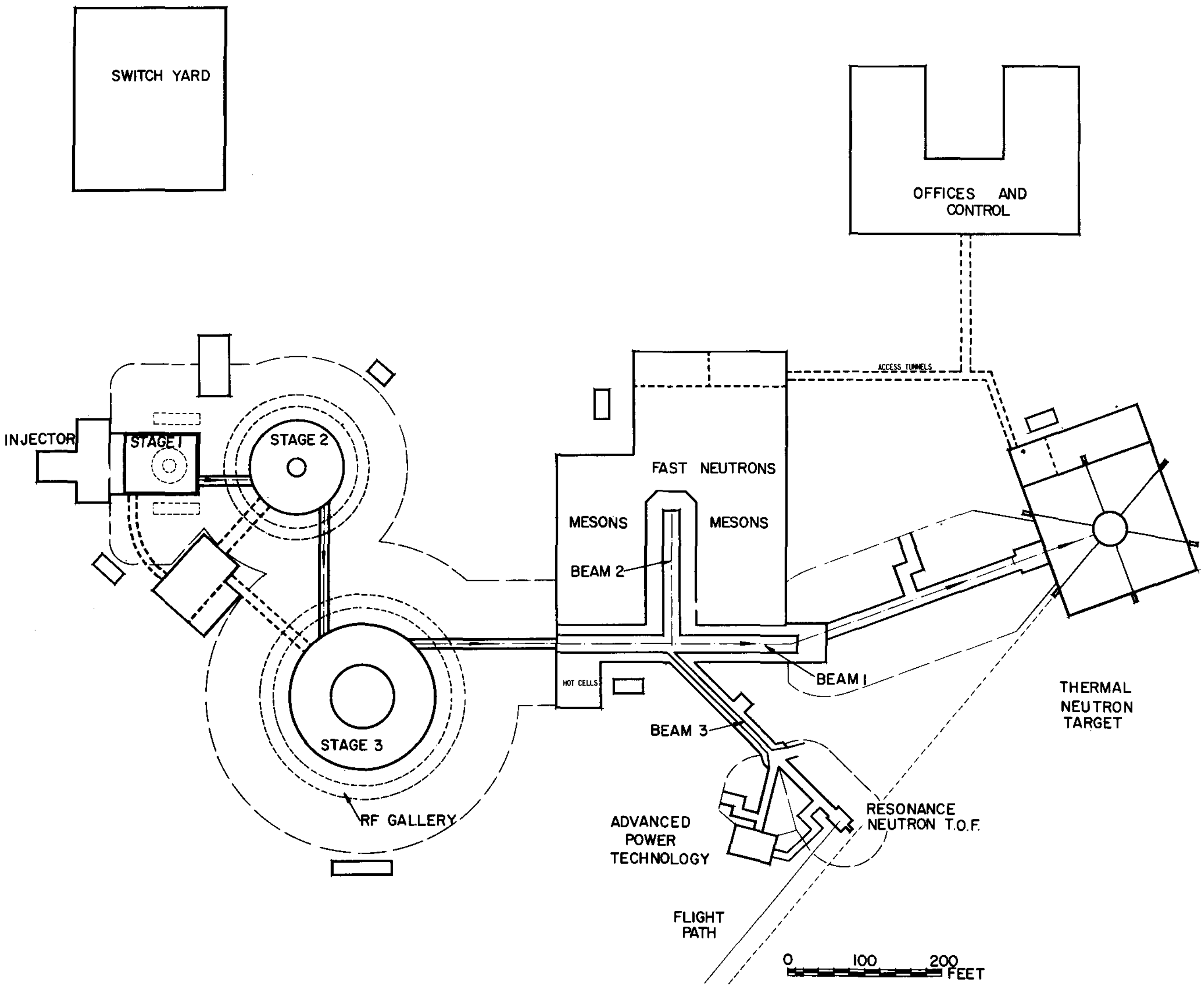

Fig. 1. Layout of ING project.

Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966

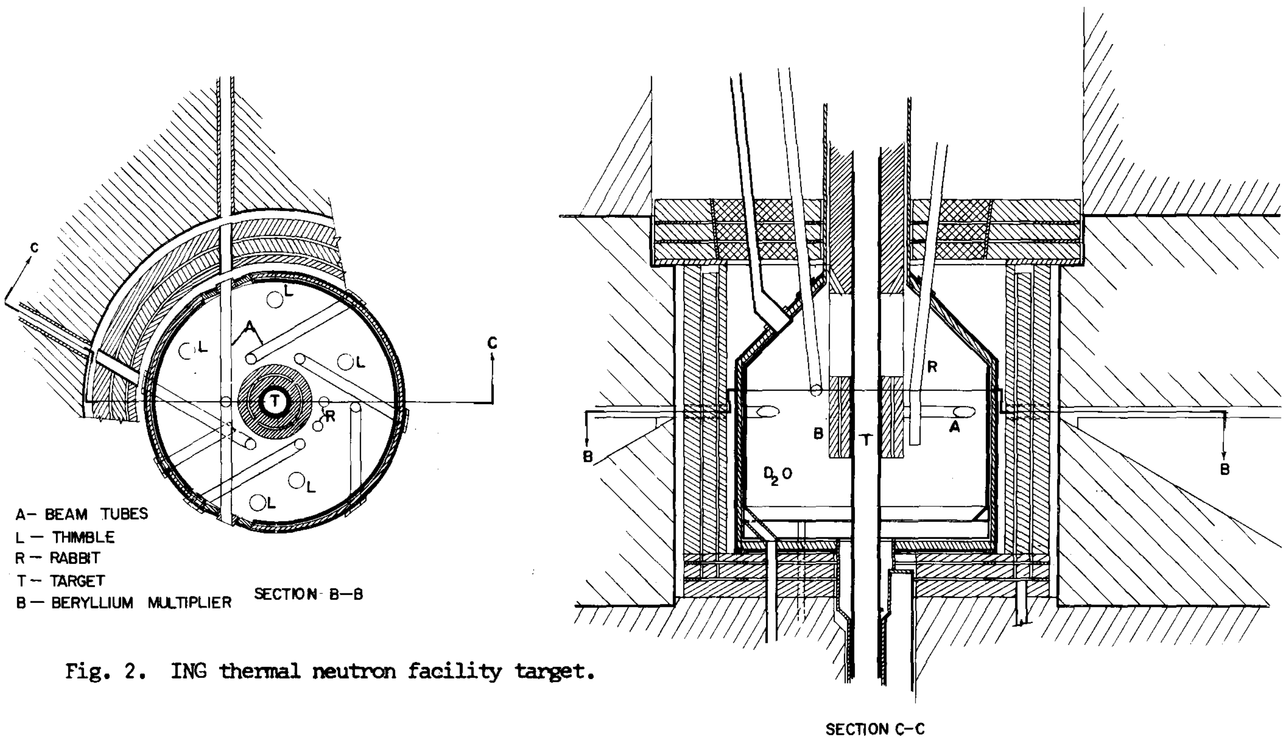

Fig. 2. ING thermal neutron facility target.

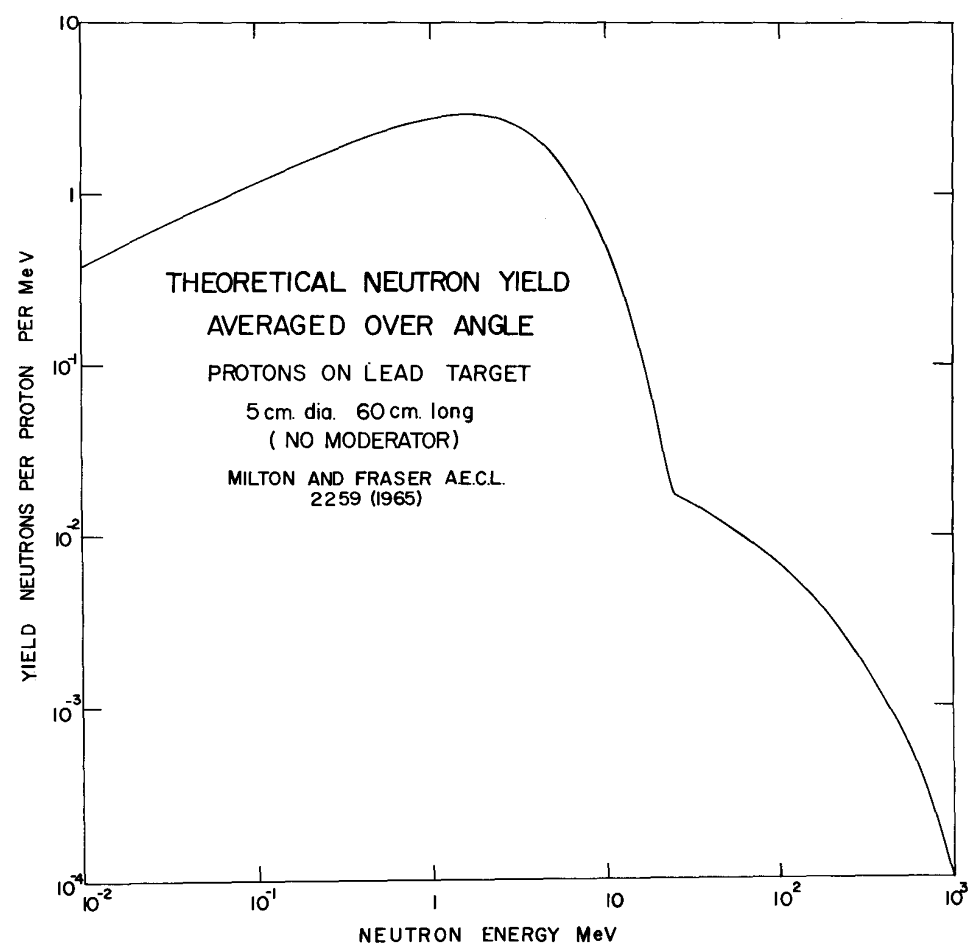

Fig. 3. Unmoderated spallation neutron spectrum.

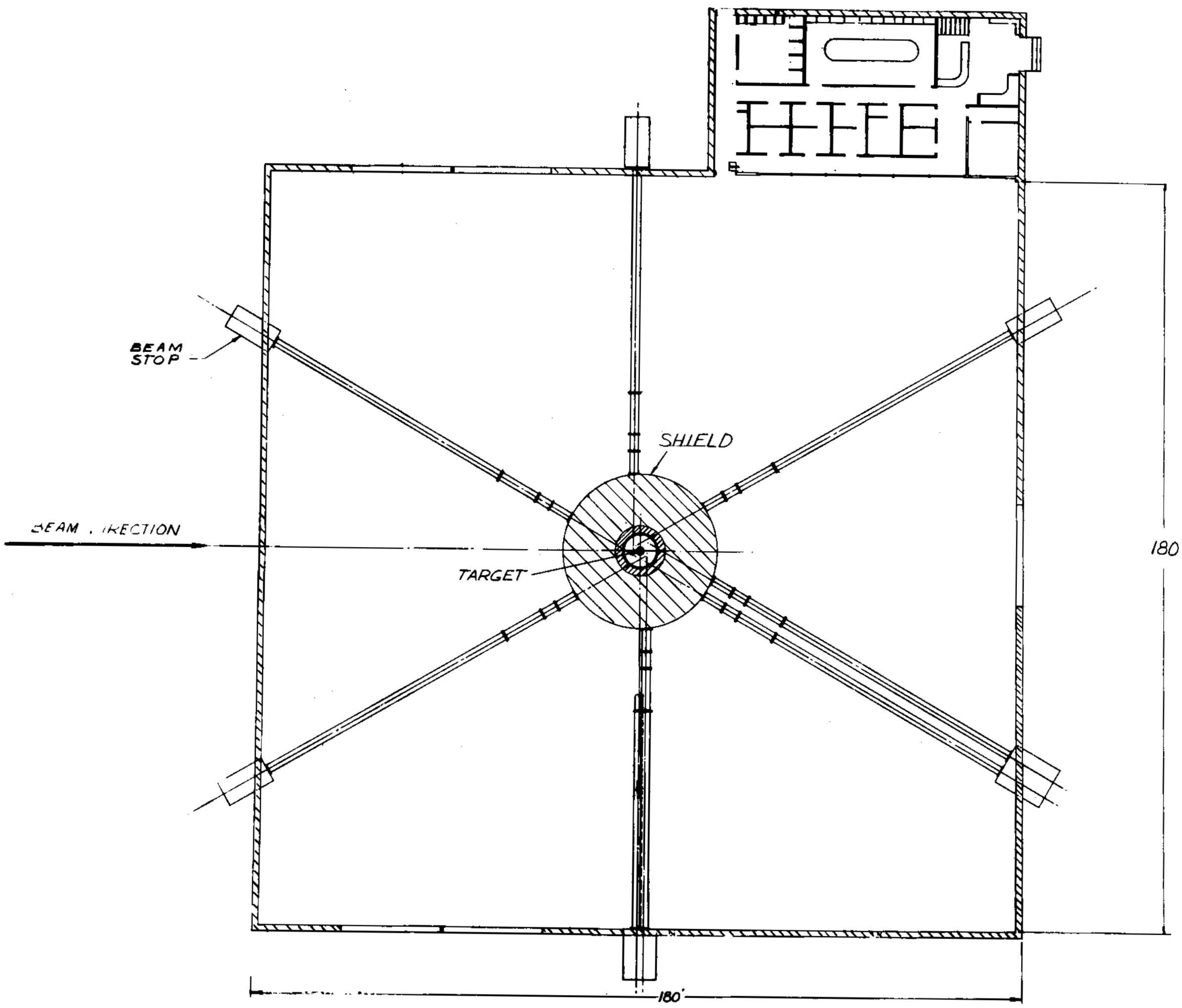

Fig. 4. Schematic plan of ING thermal neutron target and experimental area.

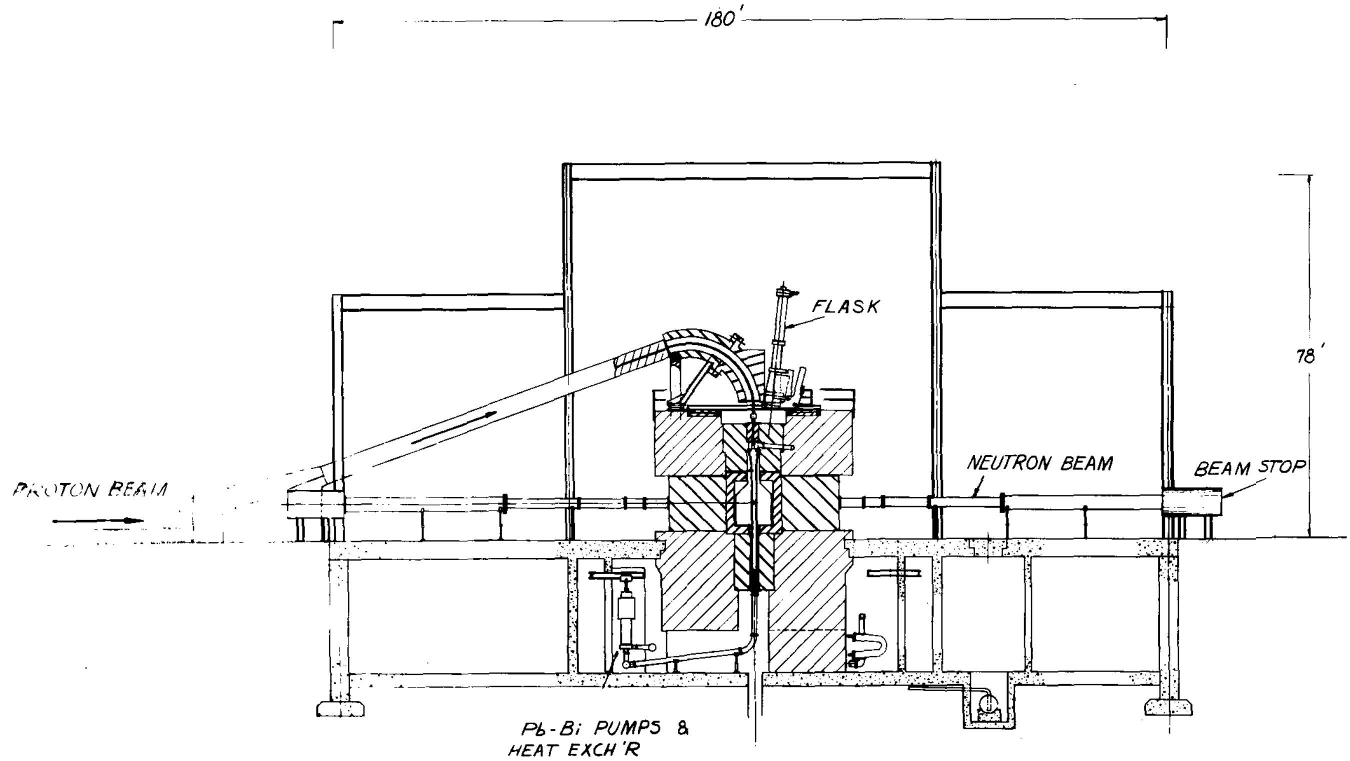

Fig. 5. Elevation view of ING thermal neutron target showing positions of proton beam transport, neutron beam tubes, flask for servicing irradiation facilities, and parts of the liquid metal circulation system.

DISCUSSION

VOGT: What fraction of the 65 mA beam would you be able to use for meson production?

BARTHOLOMEW: We contemplate using thin transmission targets in the main beam; these would be difficult to cool, but would perhaps take 1% of the beam. Alternatively, perhaps a milliamp of beam could be used for meson production if the beam is deflected to Channel 2.

VOGT: Is there no thought of using much more of the full beam for meson production?

BARTHOLOMEW: This is not impossible, but we thought that allowing about 1 mA for meson production would be satisfactory, initially.

DMITRIEVSKY: Does one obtain the greatest neutron yield from lead and bismuth?

BARTHOLOMEW: No. The largest neutron yield is obtained from uranium or thorium, but the number of neutrons per unit of heat liberated is more favorable in lead-bismuth.

LIVINGOOD: How much will it cost?

BARTHOLOMEW: This is complicated, how much do you include in the device, how much development work, auxiliary equipment, and so on. We would hope that our initial facility would cost rather less than twice as much as the Los Alamos facility.

 Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966 © IEEE 1966