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AN H^- MESON FACILITY

Invited Paper

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Abstract

With the continuing evolution of the various types of meson factories the relative merits of the H^- spiral ridge cyclotron appear to be improving. The development and design of such an accelerator has been led by UCLA. Recently three universities in British Columbia have combined personnel for a design study intended to lead to an H^- meson facility (called TRIUMF - Tri University Meson Facility). Among the various meson factories the H^- facility is the only one which combines the following advantages: (1) large duty factor; (2) variable energy; (3) ease of beam extraction; (4) use of simultaneous beams; (5) high beam quality. Until recently it faced two problems: (a) uncertainty about field dissociation of negative ions; (b) lack of polarized ion sources. Recent UCLA measurements of field dissociation and the advent of polarized H^- ion sources and axial injection into cyclotrons remove these problems. The field dissociation measurements agree with Hiskes' calculations and enable the use of higher fields than previously proposed for H^- facilities. The TRIUMF project concerns a machine whose beam characteristics (maximum energy 500 MeV; maximum beam radius 271 inches; beam current 20-100 μA) were selected for optimum use in nuclear structure experiments, for low cost and for operating simplicity.

1. Introduction

For a number of years groups of physicists across the world have been trying to arrange a marriage between their particular meson factory design and the government funding agencies. In the parade of brides the negative ion spiral-ridge cyclotron advanced by the UCLA group has for some years appeared to possess the largest list of substantial virtues. In the U.S.A. the Bethe Panel played the role of marriage-broker two years ago. While lavishly praising the major virtues of the negative ion concept the Bethe Panel also noted some of its apparent minor blemishes - in spite of which the negative ion cyclotron (along with the linac) led the bridal parade two years ago. The blemishes noted then have now largely disappeared leaving the negative ion cyclotron in a stronger position than ever. We want to report on that position and also tell you how the bride is being seduced across the border into Canada by a group of physicists from three universities in British Columbia.

2. Present Status of the H^- Cyclotron as a Possible Meson Factory.

Except for relatively minor changes the basic machine being considered by our British Columbia group is the UCLA machine[1,2]. Fig. 1 illustrates the basic magnet shape of the UCLA design and the ease of beam energy variation and beam extraction inherent to a negative ion machine.

The list of substantial virtues of the H^- meson facility are displayed on Table 1 which compares various meson factories. A similar comparison was made a year ago[2] but a number of the figures have been brought up-to-date and we have added an extra column for the particular H^- cyclotron being considered in British Columbia. The British Columbia project is called TRIUMF for Tri-University Meson Facility. The ring cyclotron whose characteristics are shown on Table 1 is that of the Zürich proposal[3] which has now been approved. The linac is that of the Los Alamos proposal[4] and the SOC is derived from Oak Ridge[5] and Chalk River[6] studies. The linac's macroscopic duty factor has been increased from 6% to 12% because of the development of side-coupled cavities. The Separated Orbit Cyclotron is retained at 5 milliamps although the use of this machine for the generation of intense neutron fluxes requires ten times greater average beam current - an increase most of which would be reflected

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in the meson production rate and part of which would be reflected in the cost. The reasons underlying the choice of beam characteristics in the British Columbia design study will be discussed below.

The main point of Table 1 is to bring into perspective the solid performance of the H^- cyclotron in the following major categories.

1. Energy Variability - Only the H^- cyclotron is fully variable in energy. The linac and SOC can be varied in steps by shutting off cavities.

2. Duty Factor - In this very important category the linac is still far from competetive with any of the cyclotrons.

3. Simultaneous Multiple Beams - The H^- cyclotron is the only one which enables a beam of 100% duty factor to be used simultaneously in more than one experimental area.

4. Extraction Efficiency - This is a problem for a positive ion cyclotron such as the Ring cyclotron. The H^- cyclotron should approach the linac and the SOC in its small amount of beam loss.

5. Beam Quality - The beam spread of the H^- cyclotron at maximum energy should be well under an MeV, even without using wedge-shaped degraders.

To focus attention on recent developments which have improved the relative position of the H^- cyclotron as a meson factory we give the following quote from the report of the Bethe Panel[7] assessing its position two years ago:

> "Special Considerations on H^- Cyclotron.
>
> On both the two primary considerations, variable energy and high duty cycle, the negative ion cyclotron is favorable. However, aside from the question of polarized ion sources, this device is limited in the energy easily achievable by a peculiar effect. The magnetic field acting on the fast ions is equivalent to a strong electric field, and in this electric field the H^- breaks up due to Stark effect. Consequently, while the H^- cyclotron may well be the cheapest accelerator at 500 MeV, it becomes rapidly more expensive around 700 MeV because the design is strained. By contrast, the cost of a linear accelerator does not change rapidly with energy, and this type of machine has the advantage that it might later be extended to higher energy so as to permit production of strange particles. This possibility of extension seems especially interesting now because it is not expected that MURA will be built.
>
> Even if the H^- cyclotron is not chosen for the Meson Factory, the Panel believes that research related to this type of accelerator, including the development of ion sources, should be continued with vigor."

Since that report polarized H^- ion sources have been developed and the problem of electric dissociation has turned out to be less serious.

Currents of up to 10^{-3} μA of polarized H^- ions at 100 keV have been obtained by Haeberli et al[8] from a conventional polarized ion source and successfully accelerated in a tandem generator. Furthermore a new method of producing polarized H^- ions, based on the polarization of H atoms in the metastable 2S state is under development in several laboratories. In preliminary measurements Donnally[9] succeeded in converting 0.6% of a beam of 500 eV protons (or 1 keV deuterons) into a well collimated beam of H^- ions (or D^- ions). Recently Drake and Krotkov[10] have shown that these ions have 60% of the theoretical polarization and have improved the conversion efficiency to 2%. The beam intensity is only 4×10^{-3} μA, but in spite of the problems associated with intense ion beams at low energies, the high conversion efficiency makes it possible to hope for beams of 25 μA polarized H^- ions[11] - 100 times the H^- current from present polarized ion sources - with an emittance acceptable to accelerators (say 10 mrad-cm). Should intense H^- beams not be attainable by this method polarized protons can still be accelerated in the H^- cyclotron simply by using it as a positive ion cyclotron at fixed energy. The estimates of Table 1 were based on the use of positive ions. However the polarized negative ion sources should improve in intensity and they make possible variable energies in the extracted polarized beam. Plans for the negative ion cyclotron will certainly include the use of such ion sources. In this connection it should also be mentioned that at Birmingham in 1965, for the first time[12], a beam of polarized ions was injected axially into a radial ridge cyclotron, successfully accelerated to full radius and extracted, without any measurable depolarization (this is of course the scheme planned for the British Columbia Facility).

The recent field dissociation measurements of Richardson et al[13] (for values of v x B similar to those of the H^- meson factory and the supporting theoretical calculations of Hiskes[14] (shown on Fig. 2) imply less field dissociation than had been previously expected[1] on theoretical arguments alone. As discussed in the next section, these findings effect a considerable economy in the negative ion machines. They also remove some doubts about its practicability. The outlook for the negative ion machines is now more encouraging than ever before.

3. The TRIUMF Project in British Columbia.

Recently a group of scientists from three British Columbia universities* have received a grant from the Canadian government for a preliminary design study of a negative ion cyclotron. The TRIUMF project to be based on this cyclotron will be proposed next year.

There are two basic physical facts which lead to the choice of beam characteristics for the TRIUMF project. The first concerns the remarkable constancy of the number of available stopped pions with the variation of the proton bombarding energy above 450 MeV. The second concerns the control over beam loss possible in the H^- cyclotron by varying the energy(to reduce electric dissociation loss) or the vacuum (to reduce gas stripping loss). The control of beam loss makes possible great flexibility in the beam current which can be handled by the H^- cyclotron.

We demonstrate first the constancy of the pion production rate which leads to a choice of rather low energy for the TRIUMF cyclotron. Fig. 3 shows the angular distribution of π-mesons for various proton energies used to bombard a carbon target. At forward angles (where a pion channel might reasonably be located) the production rate rises rapidly up to 450 MeV and then remains almost constant. While the total number of pions remains constant the energy spectrum changes with proton energy. Even though the change in energy spectrum affects the number of pions decaying in flight the actual number of pions which reach a secondary target 40 feet from the point of pion production is still remarkably energy independent. Fig. 4 illustrates this point. The bottom half of the figure shows the pion spectrum (for a C^{12} target and a pion channel at 20°) both at the primary target and at the secondary target 40 feet away for a proton energy of 550 MeV. The top half shows the pion spectrum for various proton energies at the secondary target. The total number of pions at each energy is proportional to the area under each curve and is roughly the same for each.

The research value of extra pion energy depends on the individual experiments discussed below. Quite generally, many of the most important experiments involve stopped mesons for which high pion energy at the secondary target is not advantageous at all because it implies greater range. From the point of view of the experiments the facility should have an energy greater than 450 MeV** but not necessarily much greater. The choice depends on beam intensity and cost. In the next paragraph we show that the H- cyclotron is a very flexible device as far as beam intensity is concerned. Further below we show that the accelerator cost varies roughly as the square of the energy. Therefore 500 MeV as a maximum energy is a very reasonable preliminary choice.

The ability of the H- cyclotron to easily accommodate large beam intensities arises from the detailed behavior of the two principal loss mechanisms: (1) electric dissociation from the v x B electric field seen by the H- ions; (2) residual gas stripping. Fig. 2 showed the recent electric dissociation measurements of Cahill, Richardson and Verba[13] compared to various theories. The theoretical predictions of Hiskes[14] agree well with these measurements, and give confidence in extrapolating these results to 500 MeV. Although these measurements were made at 50 MeV the magnetic field is also higher so that the value of v x B is very nearly the same as that for TRIUMF.

The variation of the electric dissociation loss with ion energy is shown on Fig. 5 which also gives the corresponding energy variation for gas stripping, the other main loss mechanism. The integrated gas stripping loss is determined by the vacuum (a total loss of 4% for 10^{-7} torr) and the dissociation loss by the magnetic field strength. (Normalized to 16% on the Figure, which corresponds to the design specifications discussed below).

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* The present design study group includes the following staff members from the Universities indicated:

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M. McMillan, K. Mann, P. Martin ,
E. Vogt (Chairman), G. Volkoff,
D. Walker, J. Warren, B. White.

Simon Fraser University:
R. Haering, B. Pate, R. Korteling.

University of Victoria:
M. Pearce, H. Dosso, G. Mason.

** For a heavier meson production target, say copper, this energy may be lower.

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The figure shows that the electric dissociation occurs only at the highest energies while the gas stripping is roughly constant with energy.

The choice of beam and accelerator characteristics now proceeds as follows. We begin by selecting a maximum energy, say 500 MeV as above. We next decide what beam loss is tolerable - this might be 20 μA * for TRIUMF. Whatever the acceptable beam loss figure we choose the total beam loss, at maximum energy to be mostly due to electric dissociation because this enable a great increase in beam power (without much loss in stopped pion intensity) merely by dropping the energy. Therefore the acceptable magnetic field of the cyclotron (and its size and cost) are determined by the maximum energy, the intensity required at maximum energy, and the acceptable beam loss. The vacuum required is determined by the intensity required at low energy and the acceptable beam loss. For the example given above (20 μA acceptable beam loss) it is possible to aim at a beam intensity of 100 μA at 500 MeV and 300 μA at 450 MeV. This is accomplished by the TRIUMF design discussed below which has 4% residual gas loss and a magnetic field for which the electric dissociation is 16% at 500 MeV and 3% at 450 MeV. One can always increase the beam intensity by lowering the energy and improving the vacuum. Alternatively one can simplify the machine operation by doing the same thing without increasing the intensity. With relatively minor adjustments the activation problems disappear, along with the beam, into the beam dump. The proposal for the TRIUMF project will likely envisage early operation of the cyclotron at beam intensities well below the full potential of the machine.

The beam characteristics for TRIUMF (discussed below) arise from considerations which lead one to a rather low maximum energy (of, say, 500 MeV) and moderately low beam current (ranging from well below 100 μA to well above 100 μA). One might think of such an H- facility as a "junior" meson factory - a low-cost, versatile facility able to make a major excursion into the territory of experiments discussed in connection with meson factories but not to bulldoze through this territory. To show which of the experiments would be possible with a 500 MeV, 100 μA H- cyclotron we list, in Table 2, the experiments considered by the Bethe Panel. In addition to the list of experiments the Table contains:
(a) the beam currents estimated by the Bethe Panel for some of the experiments;
(b) the order of importance of these experiments in the fields of nuclear structure and elementary particle physics, following the discussion in the Bethe Panel report. The assessments in the two fields are independent and the numbers 1, 2 and 3 or a, b, c are for decreasing order of importance on an arbitrary scale (selected by us to follow the discussion of the Bethe Panel Report). The numerical estimates of the Table are two years old and some of them should be revised - for example, the advent of germanium detectors has greatly increased the amount of μ -capture work possible with relatively low intensity.

The restriction in the maximum energy to the neighbourhood of 500 MeV would make the pion-pion scattering experiments impossible and limit the energy range over which pion-nucleon and nucleon-nucleon form factors could be determined. This swings the emphasis of the machine to the nucleon structure experiments which, in any event, make the dominant case for the meson factories. For the nuclear structure experiments an increase in energy above 500 MeV is unimportant. This is particularly true for the stopped meson experiments which are the most important and for which the optimum energy^2 may lie below 500 MeV.

The restriction to beam currents in the neighbourhood of 100 μA clearly does not preclude any of the important nuclear structure experiments - particularly for a machine whose intensity can easily be increased above 100 μA The important figure to remember is the extracted beam of present synchrocyclotrons (only 0.05 μA) so that even 100 μA is an enormous leap forward. In fact, for a large fraction of the experiments one could easily run the machine at lower intensity with correspondingly less activation problems. The table makes clear that the range of experiments possible for a junior meson factory are very great indeed - particularly for one whose energy and intensity are easily varied.

The Reference Design.

The design of a 500 MeV negative ion cyclotron for TRIUMF follows the earlier UCLA work^1 for a 600 MeV cyclotron. Preliminary calculations yield an optimum spiral-ridge shape similar to that of Fig. 2 except

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* This loss estimate would yield operating conditions comparable to those for the 184" cyclotron at Berkeley if it had a 5 μA loss.

that the central portions of the spiral-ridges are wider . A guide specification for this design is given on Table 3. These figures are intended only as a rough working guide.

As illustrated on Fig. 2, the magnet consists of six separate spiral hills, each with its own yoke; there is no iron in the valleys. The magnet coils are wound in a circle around the outer radius of the poles. The magnetic forces, amounting to about 1600 tons between the poles, are resisted by a central support and by the return yokes. Trimming coils consist of 17 pairs of profile coils concentric with the magnet axis and 24 pairs of harmonic coils to correct the first and second harmonics in amplitude and phase.

The vacuum tank, 49 feet in diameter and 23 inches in height, has to resist a force of 2000 tons on each cover due to atmospheric pressure. The upper cover is supported by several hundred skyhooks from a structural steel frame built into the centre post; the lower cover is similarly attached to the reinforced concrete floor. Magnet gap closure at the centrepost caused by the vacuum load was expected to be less than 13 mils in the UCLA design, causing a field variation of less than 0.1 gauss/ft. Access to the tank is through the top cover to avoid the radioactive outer wall.

The two-dee, radio-frequency accelerating system comprises eight sub-assemblies which are quarter-wavelength resonators operating at a frequency of 26 Mc/s. This is the fifth harmonic of the ion frequency. The four resonators forming one dee are tightly coupled due to the RF magnetic flux linkage and are driven by one coupling loop located between the top two resonators.

Negative ions are produced in an Ehlers hot filament source, accelerated to 200 keV in an HT set and steered into the centre of the cyclotron through the centrepost. The buncher can be used to produce a sharp pulse of injected ions when a low duty factor beam is required.

Carbon foils 3-5 microns thick may be used for stripping targets. Power dissipation in these would be of the order of 200 mW, which is easily dissipated by radiation. The target holders can be moved by remote control along tracks in the vacuum tank.

The large size of the cyclotron follows from the need to mitigate electric dissociation. In turn the size yields great simplifications in the engineering of the machine. For example the tolerance on the pole faces is approximately 1/32 of an inch per foot - which should not be difficult to achieve -- and the problem of axial injection becomes easier with large size.

There is now a large and increasing body of knowledge concerning the beam dynamics of sector-focused cyclotrons. In the case of the six-sector geometry proposed for the TRIUMF cyclotron, the situation in the central region is well understood and presents no difficulties. The only essential resonance in the radial betatron frequency (ν_r), which must be passed, occurs at some 400 MeV where $\nu_r = 3/2$. Extensive computer studies[15] have been made in this region. They show that it is possible to use a three-fold radially increasing magnetic field bump for extraction of one or two beams at this energy. More important for the H- cyclotron, however, were the parts of the work relating to the stability of the equilibrium orbit to disturbance due to flat magnetic field bumps. Several spiral angles were investigated, and it was found that even for spiral angles as large as 70° the particles accelerated through this region without difficulty, in a large area of the radial phase space. For irregularities in magnetic field which in practice could be easily found and corrected, the growth in amplitude of radial oscillation was completely negligible.

Experimental Areas and Facilities.

The full development of the experimental capability of the pion facility for TRIUMF is suggested by Fig. 6 taken from the UCLA study. It would not be expected that the full capability would be developed until several years had elapsed after initial operation. For example, Experimental Area II will likely be omitted in the initial stage of the TRIUMF project.

Fig. 6 shows two external proton beam handling systems and connected experimental areas. Both systems may be operated simultaneously with 100% duty factor and at differing energies. Experimental Area I is adjacent to a long proton beam tunnel. A provisional partitioning of the area into smaller areas for special functions is shown. The first area is the high energy low intensity pion area. A thin target will be used to supply pion beams to this area. The next area is a low energy high intensity pion area into which low energy beams from a thick target are admitted. Next is the muon channel which receives beam from a thick target. Finally there is a high energy high intensity pion area, which is

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supplied with pion beams produced at zero degrees from a thick target. Experimental Area II has a single target station which may be used to produce pions, polarized protons, or polarized neutrons. The beam transport system for this area is designed to produce a high resolution primary proton beam for high resolution proton-nucleus scattering and reaction experiments.

Dispersionless Extraction.

The extracted beam from the H^- cyclotron will be dispersed by the fringing field of the cyclotron. This dispersion can be removed by the introduction of appropriate asymmetries in a subsequent bending system to form a totally achromatic system from stripper to beam line. The parameters of such a system have been calculated[16] and the results are incorporated in the first sets of magnets shown on the two external beam lines shown on Fig. 6.

A high resolution beam is suggested for Experimental Area II for experiments requiring very small energy spread, e.g. proton induced reactions in nuclei such as (p, 2p). In this beam, a wedge-shaped degrader can be used to narrow the emerging beam energy spread of ± 0.5 MeV so that all the current is passed to the experimental areas with a full width at half maximum of 200 keV. Multiple scattering in the degrader will increase the phase area in the resulting beam by less than 10% and is therefore negligible.

Cost of the TRIUMF Project.

The cost of the TRIUMF project is roughly estimated on Table 4. The costs are based on the detailed estimates of the UCLA study[1] scaled down to the facility being considered for TRIUMF. The cost reductions from the UCLA estimates are achieved, for example, by omitting one of the two experimental areas, by reducing the maximum energy to 500 MeV effecting a considerable reduction in accelerator size, and by reducing some of the general costs in keeping with scope of the British Columbia project.

The low maximum energy of the TRIUMF reference design arises, in part, from the rapid variation of accelerator cost with maximum energy. A simple dimensional analysis can be made of the variation of the of the accelerator with the maximum energy and the maximum electric dissociation in the design. To look at this we recall the expression for the electric field, $\mathcal{E}$ MV/cm, corresponding to the maximum magnetic hill field B_H in kG,

$$\mathcal{E} = 0.3\,\beta\gamma B_H\ .$$

Also the mean value of the product of field and equilibrium orbit radius is given by

$$\overline{B\rho} \approx \beta\gamma$$

The momentum, $\beta\gamma$, expressed in terms of ϵ = kinetic energy/M_0C^2 is

$$\beta^2\gamma^2 = \epsilon\,(2+\epsilon)$$

The axial focussing condition in simple form yield

$$\nu_z^2 = F^2(1+2\tan^2\alpha) - \beta^2\gamma^2 \equiv F^2a^2 - \beta^2\gamma^2$$

where F is the flutter (defined by $B_H = (1+F)\bar{B}$) and α the spiral angle of the middle of the hill. The field shape is designed so that ν_z^2 is kept small (~ 0.04). Thus we have

$$\beta\gamma \sim Fa$$

so that we can finally write

$$\bar{\rho} \approx \frac{\epsilon\,(2+\epsilon)}{\mathcal{E}}\left[1 + \frac{\sqrt{\epsilon\,(2+\epsilon)}}{a}\right]$$

Since a is a large number ($\sim$ 20) we can ignore the variation of the square root term if the changes in design energy are 30% or less.

For corresponding fractional changes in the radius we can assume that the cost, C, of the major components (magnet, dee and RF structure, etc.) varies as the square of the radius. Thus we have

$$C \sim \bar{\rho}^2 \sim \frac{\epsilon^2(2+\epsilon)^2}{\mathcal{E}^2}$$

Then we can write an expression for the fractional change in cost of the accelerator,

$$\frac{\Delta C}{C} \approx (2+\epsilon)\frac{\Delta\epsilon}{\epsilon} - \frac{2\,\Delta\mathcal{E}}{\mathcal{E}}$$

in terms of the fractional change in the maximum energy and the fractional change in the electric dissociation field. From the curve of Hiskes one concludes that the probability of electric dissociation λ varies with the electric field in such a way that λ is multiplied by a factor of two when the electric field increases by $\frac{\Delta\mathcal{E}}{\mathcal{E}} = 0.028$.

We conclude, for example, that for a constant fraction of the H^- ions lost by electric dissociation, an increase of 10% in the design maximum energy will require a 25% increase in the cost. On the other hand, at constant energy, if we accept a four-fold multiplication of the electric stripping loss, we reduce the cost by 11%. It is cost arguments of this kind combined with evaluation of research potential which establish the TRIUMF design envisaged above.

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Table 1 - Comparison of Meson Factories

	H^- Cyclotron				
	TRIUMF	UCLA	Ring Cyclotron	Linac	Sep.Orbit Cyclotron
Energy (MeV)	500	600	510	800	800
Energy Variable MeV	175-500	200-600	No	200-800	375-800
Duty Factor Macrostructure	100%	100%	100%	6-12%	100%
Average Current (mA)	0.1**	0.6*	0.08	1.2	5
Average RF Power (MW)	0.83	1.3		6.1	15
Overall Size of Accelerator (feet)	56 diam.	70 diam.	43 diam.	2000 x 17	360 x 180
Polarized Protons*** per second	1.2×10^{11}	1.2×10^{11}		2.4×10^{10}	4×10^{11}
Simultaneous Multiple Beams	Yes	Yes	No	No	No
Cost of Accelerator (Millions of dollars)	4.5	6.6	7.0	20.0	27.1
Cost of Project	12.8	19.8	21.3	55.0	65

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* Current rating 0.6 mA from 200-550 MeV and 0.2 mA at 600 MeV.

** Current rating at 500 MeV: higher currents possible at slightly lower energy.

*** For comparison purposes, a polarized source strength of 2×10^{12} protons per sec. is (optimistically) assumed in each case.

TABLE 2. Experiments described in the report of the Bethe Panel[7], including experiments discussed in the text of this report. For some of these experiments the Bethe Panel report gives estimates of the proton beam current required for practical counting rates. These estimates are given in the second column of the table and should be compared with typical figures of 0.05 μA in existing synchrocyclotrons and 100 μA proposed for TRIUMF. The third and fourth columns give the order of importance attached to these experiments by the Bethe Panel, expressed here in the form 1, 2, 3, or a, b, c where the lowest figure or letter implies highes priority. The two assessments, in the fields of nuclear structure and particle physics, should be regarded as independent, and the scales of importance are arbitrary.

Footnotes are: * requires high beam energy and intensity,
** no intensity estimate given in Bethe Panel Report, but the 100 μA of TRIUMF should clearly be sufficient.

Experiment	Required Current A	Order of Importance	
		Nuclear Structure	Particle Physics
1. Pion-nucleon elastic scattering			
(a) π -p	5-50		a
(b) π -n	500-5,000		a
2. Pion-pion scattering	*		a
3. Nucleon-nucleon force			
(a) C_{nn} in (p,p)	0.5	2	a
(b) spin correlation (p,p)	50	2	a
(c) triple scattering (n,p)	50	2	a
4. Meson Production	**		b
5. Elastic scattering by nuclei	**	2	
6. Various nuclear form factors			
(a) scattering experiments	**	2	
(b) angular correlations e.g. $Ca^{40}(p,p'\gamma)$	100	2	
7. Quasi-free scattering e.g. (p,2p) reactions	1-10	2	
8. Cluster rejection	1-10	2	
9. Pickup reactions	1-10	2	
10. Pion charge exchange			
(a) isotope production	**	3	
(b) pion detection	100	2	
11. Muon scattering	1,000	3	
12. Pion-capture reactions	**	1	
13. Pi-mesic atoms	**	3	
14. Mu-mesic atoms			
(a) X-ray studies	5-50	1	
(b) capture by complex nuclei	0.5-5	1	
15. Muon capture by nucleons	50		a
16. Stopped pions e.g. rare decay modes	**		b
17. Stopped muons e.g. Michel parameter	**		b
18. Neutrinos	1,000		b

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Table 3 - TRIUMF Guide Specification.

Maximum Energy	500 MeV
Maximum Beam Current	100 μA at 500 MeV 300 μA at 450 MeV
Maximum Beam Loss	20 μA at 500 MeV
Maximum Beam Radius	271"
Magnet	
Number of hills	6
Total Weight of Iron	2440 tons
Magnet gap	25"
Ampere Turns	635,000
Power	2300 kW
Conductor Weight	70 tons
No. of profile coil pairs and power	17 - 118 kW
No. of harmonic coil pairs and power	24 - 0.60 kW
Dee Voltage, peak to ground	100 kV
Max Voltage gain per turn	400 kV
Harmonic	Fifth
RF Power Amplifier Output	830 kW
Design Vacuum	5×10^{-7} torr
Baking Temperature of Dees	100°C (212°F)
Injector Energy	150 keV (300 keV available)
No. of Extraction Targets	2
Extraction Energy Range	175-500 MeV .

Table 4 - Cost of the TRIUMF Project

General Costs	2.72×10^{6} dollars
Accelerator	4.50×10^{6} dollars
Buildings and Shielding	4.38×10^{6} dollars
Experimental Facilities	1.20×10^{6} dollars
Total	12.80×10^{6} dollars

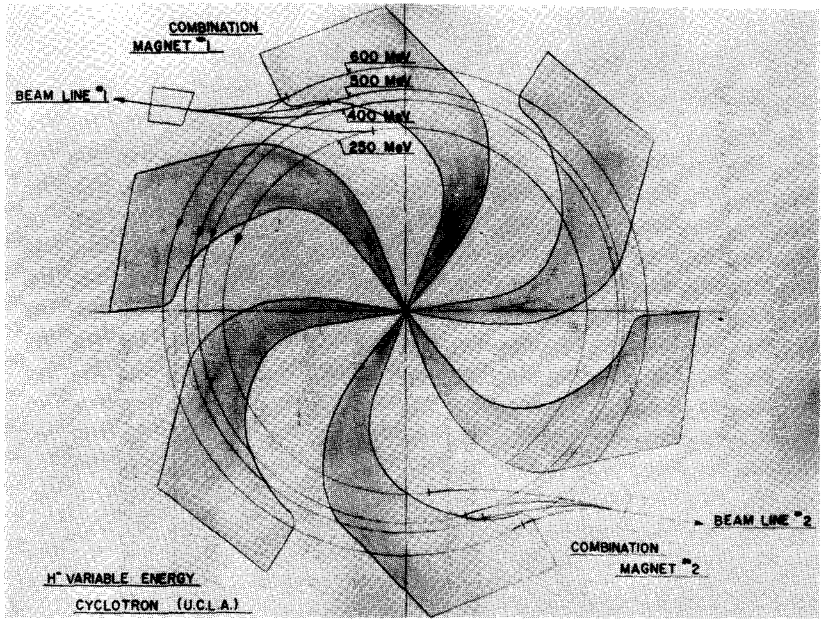

Fig. 1. The shape of the magnet for a 600 MeV H^- cyclotron as designed at UCLA. Orbits and extraction at various ion energies are also shown.

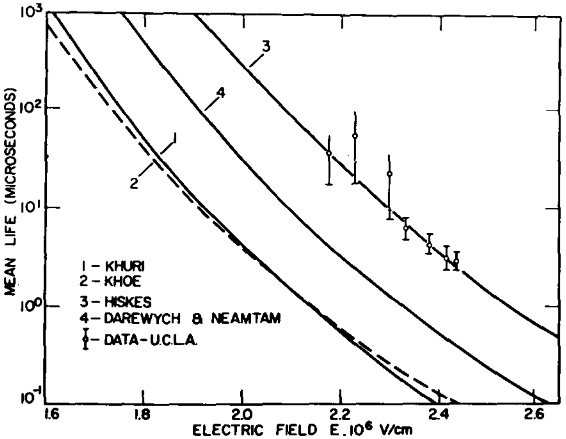

Fig. 2. Lifetimes of H^- ions in an electric field. The measurements of Cahill et al[13] are compared to various theoretical calculations.

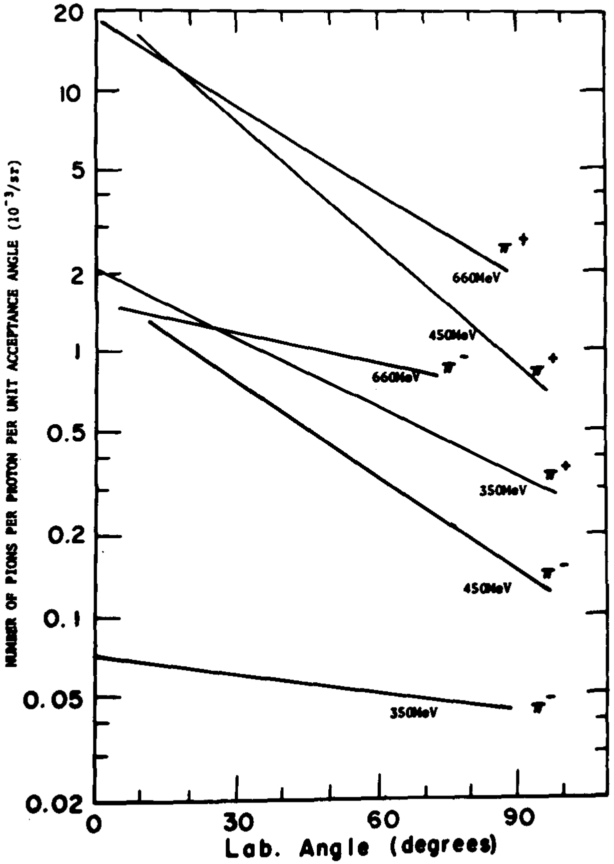

Fig. 3. Angular distributions of positive and negative pions for various proton energies.

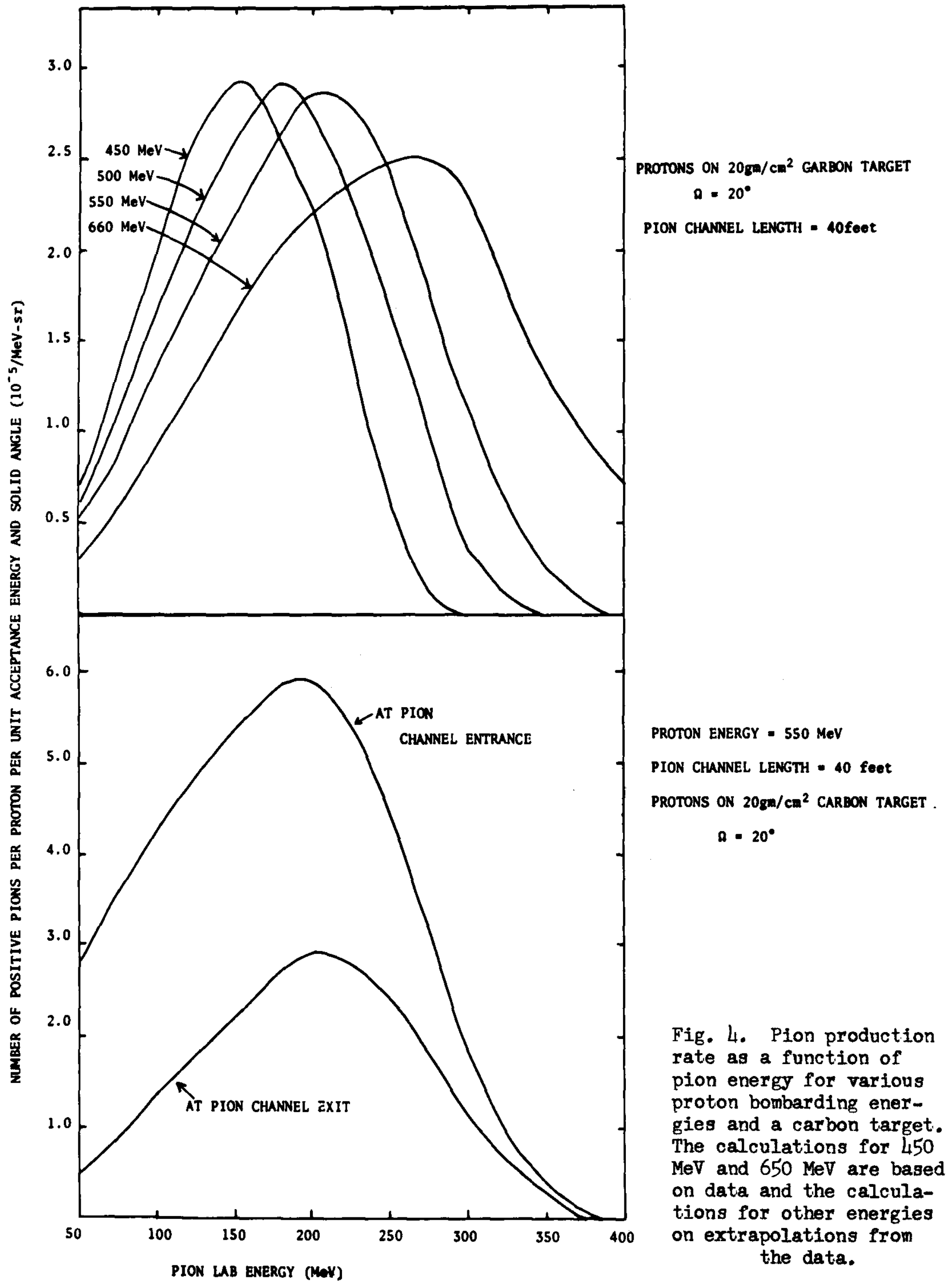

Fig. 4. Pion production rate as a function of pion energy for various proton bombarding energies and a carbon target. The calculations for 450 MeV and 650 MeV are based on data and the calculations for other energies on extrapolations from the data.

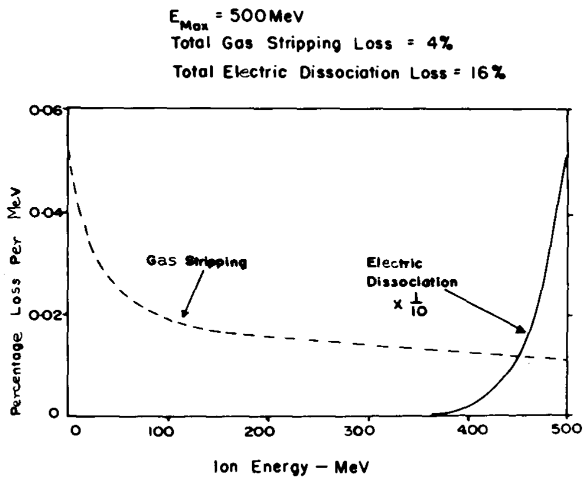

Fig. 5. Gas stripping and electric dissociation losses at various ion energies in the H⁻ cyclotron. The curves are normalized to a total loss of 4% for gas stripping and 16% for electric dissociation.

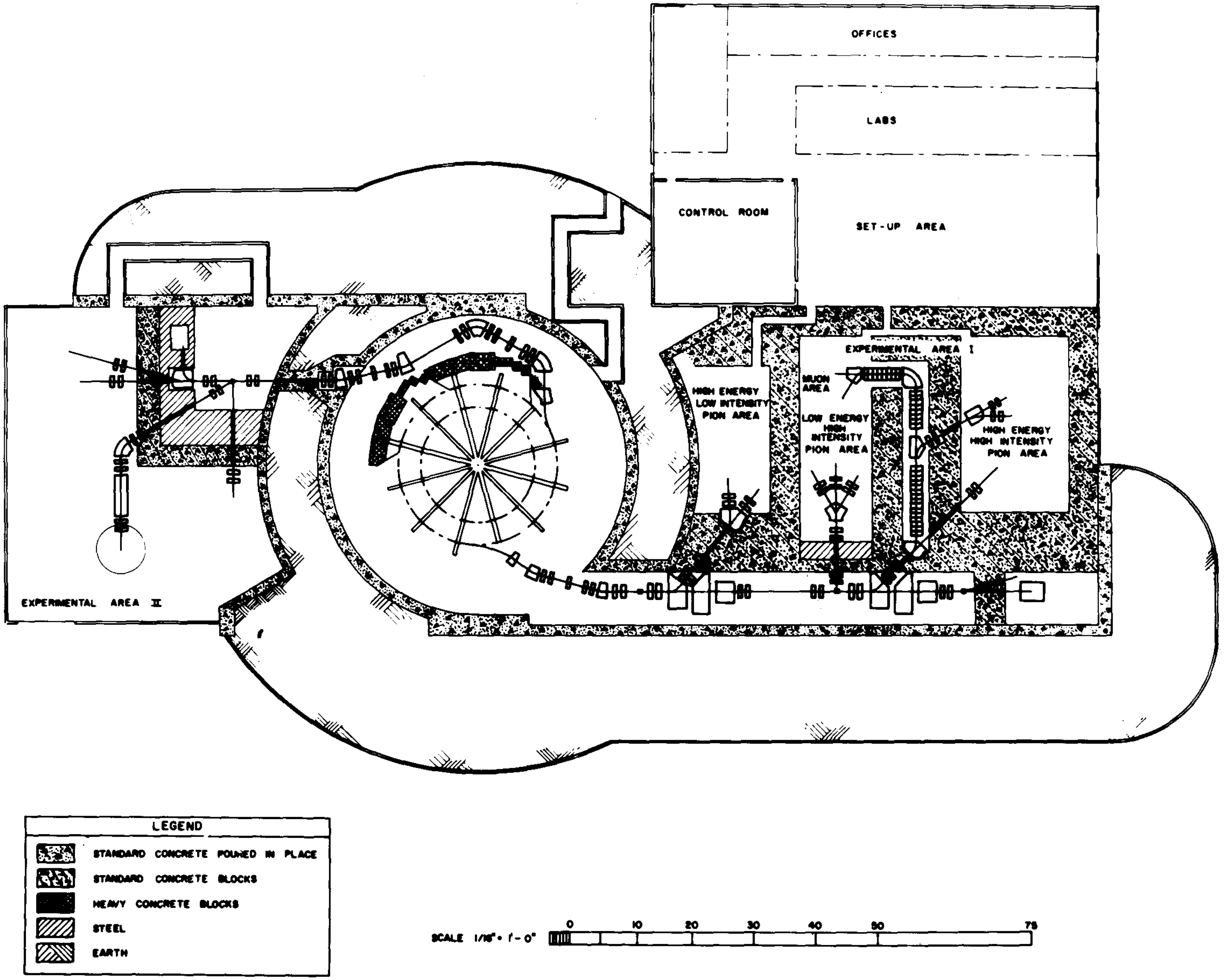

Fig. 6. Layout for the UCLA H⁻ facility.

DISCUSSION

OHNUMA: Since this is a cyclotron conference, I see very very few linac men here. It doesn't seem quite fair to attack the linac in this kind of a conference, but referring to last year (IEEE conference in Washington), many of you may remember the heated discussion between Professors Richardson and Hughes about the relative merits of the linac and the H^- cyclotron. I believe that we will have to wait another ten years to find out, really, which machine produces more physics.

In connection with the Los Alamos linac, we are studying very hard about the beam stretcher which was mentioned by Dr. Brianti today; it does not seem entirely impossible to increase the duty factor.

I am also concerned about the intensity. For example, at CERN the linac injector is now getting about 50 to 60 mA intensity, and Brookhaven's new injector is going to be about 100 mA at 200 MeV. So, when the linac people talk about intensity, it is very honest intensity, Los Alamos can easily get an average current of 1. 2 mA, even for 2% duty factor. I really can't believe that your 100 μA at 500 MeV for H^- cyclotron is based on the same kind of reliability.

VOGT: I think one is willing to concede that for very high intensities the linac has some advantages. On the other hand, as far as the duty factor is concerned, you said very casually, "increased by a large amount." That means, of course, if you can get 50 million dollars a year for cavities, or something like this. The problem, I think, is that there is no physical principle which prevents the linac from being turned on for a much larger fraction of the time. It's just a question of whether the cavities are reliable enough, and I don't think that that is a very easy problem. You may increase the duty cycle by a factor of 2 but you are still very far from CW.

OHNUMA: I was not thinking about increasing the duty factor of the linac itself, but stretching the beam with some kind of storage ring.

RICHARDSON: The possibility of storage rings has been investigated, of course. The only satisfactory storage rings would be to put the particles in as negative ions, and then extract them by stripping, because otherwise there is the same trouble of inefficient extraction as with ordinary storage rings, if you want a large duty factor. Also, there is no evidence that a linac can work with a duty factor larger than 1% and an energy higher than 70 MeV. According to your criteria, one would say that since it hasn't been done, there is no evidence that it could be done.

In the situation that we have, as far as the negative-ion cyclotron is concerned, Ehlers has produced beams of 5 mA of separated H^- ions, and Powell reported yesterday that he is getting about 5% of the injected beam out of his cyclotron, and he said that we should talk in terms of 10%. So, it seems to me that 5 mA times 10% is quite a little bit more than the 100 μA we propose.

TELEGDI: I missed the point concerning storage rings. It has appeared to me for quite some time that the type of storage ring described here today, in conjunction with the CERN machine, would be very effective in conjunction with the linac, in which case you would have the current and the duty cycle all at once, and you could work with the thin target, which does not work with the linac, to use the beam effectively. The combination of such a storage ring with the linac would yield every advantage, and you would be assured that you would be injecting into this ring a beam of high phase-space quality. Now this ring is advertised to cost 2 million dollars at 500 MeV. It seems to me like a small amount of money compared with construction of a 500 MeV high-intensity linac.

RICHARDSON: The point here is that you have the problem of getting the particles out of the storage ring, either with a large duty factor, or with high extraction efficiency. These have not been accomplished at the same time. That is, you can get a high duty factor in a storage ring, obviously, but then the question of getting them out is still the same problem as extraction from a regular synchrotron.

TELEGDI: That problem refers only to the protons themselves.

RICHARDSON: Then you might as well have a cyclotron to begin with; if you leave the protons in the storage ring they will activate it.

KHOE: In the Los Angeles meeting (1962) the experimental measurement reported gave a dissociation field that was about four times smaller than you now show in your slide?

RICHARDSON: Those measurements had a very large probable error, and they were confused by other losses.

KHOE: But that doesn't account for a difference of 4; not more than 2. And, of course, this is important in the cost estimate. Are you sure that this measurement is the correct one?

RICHARDSON: Yes. It all depends on a very simple and straight-forward point. If the electric dissociation has the value which your calculations indicated, then we could not get the external beam in the UCLA machine which we have. It is that simple. Furthermore, the Manitoba machine, which has just a slightly lower maximum hill field than we have, observes no electric stripping at all. This would also be inconsistent with your calculations.

LIVINGSTON: It seems to me that in a meeting of this sort, in discussing all these machines, we should all be very candid about the relative advantages and disadvantages of different machines, and it seems to me that our present speaker very skillfully convinced us that all the disadvantages pointed out by other groups had been, somehow, wiped away. I think, however, that a machine which has a 20% loss in it is really at a little bit of a disadvantage, even if you can get by with it. Another point that was not mentioned is that it would be extremely valuable if you could extract H^- ions as H^- ions and use them, then, in high-resolution spectroscopy, I believe you cannot do that in the H^- machine described.

VOGT: Let me comment on the first point. We selected the 20% loss because of the question of cost. It wouldn't cost us much more at all to have a much lower beam loss, even at the maximum energy. Even in the example I gave you, if we dropped the energy by only 50 MeV the beam loss drops to about 6%, not 20%. If we find during the coming year that this is really such an enormous advantage, we could slightly improve the vacuum, make a slightly larger maximum field, and control the loss. The flexibility is a very important feature of the H^- machine.

LIVINGOOD: Don't you have to bake your dees to get 10^{-7} vacuum?

RICHARDSON: In this connection, the plan is to bring the dee structure up to just below the boiling point of water.

LIVINGOOD: Does the pump down take several days, or hours?

RICHARDSON: According to the engineering information it is somewhere between hours and a day. There has been a lot of experience in this connection with the Space Project program, where very large volumes are taken down to very low pressures, something like 10^{-9} torr.

LIVINGOOD: There is less opportunity for gas trapping in welds.

VOGT: The gas stripping, which was 4% for 10^{-7} torr, doesn't really do much harm, because most of it occurs at low energy, and all the ions go to the outside of the machine. Therefore, I think one could live with far greater than 4% gas stripping in this machine. One would not be able to go above 100 μA very easily, but it is not I think as serious a problem as electric dissociation.