COMPARISON OF VARIOUS CIRCULAR ACCELERATORS AS MESON FACTORIES

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For the purpose of this discussion a meson factory will be defined as a proton accelerator in the energy range 400 -800 MeV with a current output some hundred times greater than the present output of the FM cyclotrons in this energy range. The reasons for this choice of energy range have been discussed extensively[1] and are connected with the prime objective of the meson factory, which is considered to be the copious production of pions and muons. The actual choice of energy within this range is dependent on a detailed examination of the proposed experimental program in conjunction with the economics and performance characteristics of the proposed accelerator.

Extraction of large fractions of the internal beam has been achieved on the electron models and also on the 88 inch cyclotron at Berkeley[2] by resonance extraction using a deliberately introduced first harmonic where $\nu_r = 1$. The quality of these extracted beams, at least as initially obtained, was not particularly good, but recently a better quality extracted beam has been obtained by making use of second-harmonic excitation of the $\nu_r = 2$ resonance on Analogue II[3]. Extraction efficiencies of 75 - 80 percent have been achieved using an electrostatic septum simulating a magnetic channel.

The average field of a SF cyclotron for 700 MeV rises by a factor of 1.75 from the center to the extraction radius. Changing this rise by a significant factor to vary the energy of the beam would require large auxiliary coils which would greatly increase the expense of the cyclotron and which would be difficult to shield from radiation damage. For this reason energy variation in the SF cyclotron with H^+ ions will probably be limited to 2% or less.

The choice of the mean field at the extraction radius is an important point in the design of the magnet for a sector-focusing cyclotron. There are a number of persuasive arguments which make the choice of the lowest possible value of the mean field the most desirable one. These are :

1) By lowering the mean field the scale of the magnet is increased, thus increasing the size of the septum or magnetic channel which will intercept a given fraction of the beam. In other words, the distance between successive turns in the resonant extraction is increased.

2) The problem of injecting ions at the center of the cyclotron is simplified by reducing the magnetic field; the radius at injection is increased and the gain in radius during the first turn is also increased.

3) A larger flutter factor can be obtained at a smaller mean field. This means that

the maximum spiral angle can be reduced, which is a desirable situation for the use of resonant extraction.

At UCLA a series of paper designs were made of magnets for the acceleration of protons to 700 MeV, based upon model-magnet data. The conclusion of this study is that the magnet cost is substantially independent of the magnetic field in the 10 - 20 kG range. Thus, there is no great economic reason to favour a high-field design, and the arguments mentioned above become decisive in favour of a low mean field.

There are a number of advantages which accrue from the central injection of the ions to be accelerated in the cyclotron. These include : 1) a reduction in the initial amplitude of radial oscillation; 2) some control over the phase at injection and therefore a certain measure of control over the microstructure time variation of the beam. Associated with these points will be an improvement in the quality of the beam at the extraction radius and, therefore, an improvement in the fraction and quality of the extracted beam.

The H^- Sector-Focusing Cyclotron

Considerable experience has been gained in the last year in the acceleration of H^- ions in cyclotrons. Extension of this concept to the energy appropriate to meson factories was a natural development[4]. A program at UCLA involving computing, model-magnet tests and RF model measurements has resulted in a 700 MeV design having the following characteristics. A maximum hill field of 5 kG and a mean orbit radius of 34 ft require the use of 7000 tons of steel, 110 tons of copper and 3500 kW of power in the magnet. The design has been engineered to obtain a pressure of 2×10^{-8} torr, at which there will be a 1% loss of beam due to gas scattering. The radio-frequency system employs two straight-edged dees with 100 kV dee to ground, giving 400 KeV energy gain per turn. This requires a d.c. power of 1000 kW plus 100 kW for every 100 μA of beam. The negative ions are injected at 500 KeV, where they have a radius of curvature of 16 in. and the radius of the next turn is 21 in. H^- beams as large as 2 - 5 mA have been produced and accelerated by K. Ehlers[5] at Berkeley.

There are a number of important advantages which are possessed by the H^- SF cyclotron.

1. Flexible duty factor. Under normal operation the macrostructure factor is 100% and the microstructure factor is 30 - 40 %, although at maximum energy the microstructure factor can be increased to 80% by the use of special techniques associated with the stripping process[4]. In the other hand, for the smaller number of experiments using time-of-plight techniques, a sharp time structure can be produced from the 500 MeV injector.

2. High beam quality. Experience with the UCLA and LRL cyclotrons has shown a decrease in amplitude of the axial and radial oscillations as the radius is increased. This result holds true provided unwanted resonances are avoided. The same statements

apply to Analogue II. Central injection of the ions should improve the quality of the initial beam, and so it seems justified to expect that careful attention to the magnetic field will result in axial and radial amplitudes of 1/8 in. For the H^- SF cyclotron this will result in an axial beam quality of 1 mm mrad and a radial quality of 5 mm mrad. An important advantage of the negative ion cyclotron is that the high quality of the internal beam can be essentially preserved during extraction since the negative ion beam can be stripped and brought out along the gradient of the magnetic field. In the case of the conventional SF cyclotron, however, resonance extraction and the subsequent motion through the fringing field is bound to affect the beam quality adversely. Another possibility for extraction of the H^- beam is to neutralize it by passing it through a very thin foil or through a strong magnetic field. In using the magnetic field to dissociate the H^- ion one must take care to provide a sharp strong bump which will ensure dissociation before the ion trajectory has changed very much in direction. Otherwise the beam quality would be adversely affected. A bump field of 15 kG corresponds to a mean life for dissociate of 10^{-12} s; this would be satisfactory.

3. Variable energy. By changing the radial position of the stripping foil it is possible to vary the energy of the extracted beam from 700 MeV down to about 200 MeV.

4. Simultaneous beams. It is possible to erect a radially thin stripping foil at a radius corresponding to 400 MeV (say) which extracts a fraction of the beam at this energy while allowing the rest of the beam to continue and to be extracted at high energy. Or the two beams could have very similar energy. Both beams could have a high duty factor, in contradistinction to the situation when a switching magnet is used on a conventional external beam.

5. Low induced radioactivity. Since the gas-scattering beam loss can be made negligible and since the extraction process has an efficiency of 100% the amount of beam loss inside the accelerator is determined by the electric (magnetic) dissociation. By choosing a sufficiently low peak hill field the induced radioactivtiy can be made as small as desired.

The FM Cyclotron with Sector-Focusing Fields

Although it is likely that the output of the conventional FM cyclotron can be materially improved[6)] by raising the dee voltage and changing the source geometry, it seems probable that an FM cyclotron which makes some use of the sector-focusing principle would have several marked advantages over the conventional machine. In the first place the magnetic field can be tailored so that only a modest amount of frequency modulation need be employed. Thus, a higher repetition rate and a higher capture efficiency may be used and, in fact, the whole frequency modulation problem can be reduced to one which may be handled by the use of ferrite. In the second place the extraction of an external beam appears to be more successful in the presence of the sector-focusing magnetic field. Resonance extraction at $\nu_r = 1$ (spill beam), 3/2, and 2 can be used to obtain an external beam, and there seems to be no reason why this technique should not also be applicable in the presence of frequency modulation, although because of the lower energy gain per turn, the fraction of internal beam brought into a magnetic channel would probably be smaller than without frequency modulation.

The remarks concerning the desirability of a low mean magnetic field are also applicable to the FM/SF cyclotron. Let us consider a design where the mean magnetic field rises from 5.7 kG to 9 kG, and thus requires 10% frequency modulation. The curve of ion frequency versus time in Fig. 1 corresponds to a mean energy gain of 100 KeV per turn. It is worth pointing out that this same magnet and RF system could be used for the acceleration of deuterons to 440 MeV and alpha particles to 880 MeV without any change in the magnetic field. The betatron vertical and radial oscillation frequencies ν_z and ν_r are dependent solely on the shape of the magnetic field; thus, if the field is vertically focusing and produces the appropriate resonance at $\nu_r = 2$ for extraction for 700 MeV protons, it will do the same for 440 MeV deuterons and 880 MeV alpha particles. The isochronism condition is not satisfied, of course, and the required frequency modulation curve is shown in Fig. 1 for the same dee voltage as in the proton case.

The FFAG Ring Accelerator

Several papers discussing FFAG accelerators are being given at this conference, including one directly addressed to their application as meson factories. The average beam current to be expected can be calculated from the space charge limit, the angular- and energy-acceptance of the injected beam, and the repetition rate attainable from the RF system. A time average circulating beam of 100 μA should be quite attainable.

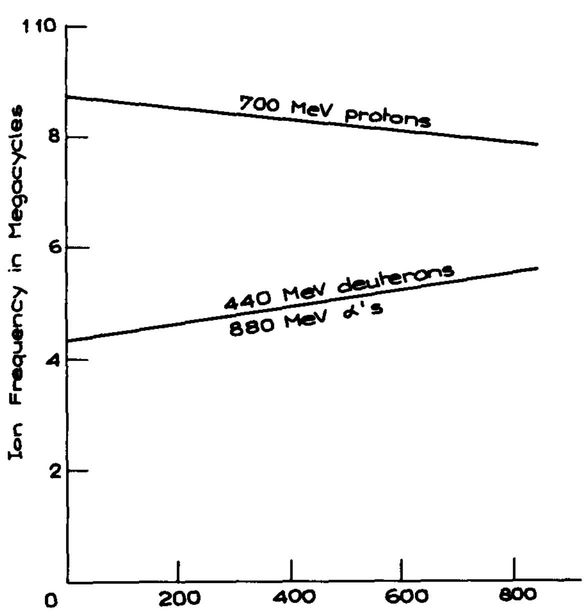

Fig. 1 Frequency-time curves for FM/SF cyclotron.

There are at least two methods of extraction which can be considered. Single-turn extraction has been demonstrated and an efficiency of some 80% is a reasonable expectation for this method. However, the duty factor in this case would be very poor, consisting of a pulse 100 ns long every 10 ms. Continuous extraction of the circulating beam has not been demonstrated, but it seems reasonable to suppose that efficiencies of 30 - 50% can be achieved. The use of an internal target for meson production can be invisaged, both for negative pions (obviously) and for positive pions which can leave the machine along the valleys where the magnetic field is close to zero and with production angles down to 20° from the forward direction. By "stacking" the beam at the final energy a microstructure duty factor of 100% and a macrostructure factor of 50% can be achieved for an internal target which is moved slowly into the stacked beam. Unfortunately the resulting radioactivity induced in the accelerator when the beam is stopped in an internal target is a very serious problem, so serious, in fact, that one is reluctant to adopt this method of operation.

The FFAG ring requires a 20 MeV linear accelerator as an injector; however, it should be pointed out that it can also be used for the acceleration of heavy ions. A Hilac-type injector would serve the dual purpose.

The AG Synchrotron

Although an AGS in the energy range considered here would be a useful and versatile accelerator, it appears unlikely that one can guarantee at the present time output currents large enough to qualify it as a meson factory.

The Separated Orbit Cyclotron

The "Beehive" or separated-orbit cyclotron has been proposed by F.M. Russell[7]. This accelerator would have an important advantage over the conventional linac as far as duty factor is concerned and would have equal accessibility to the beam. It is claimed that the capital investment for a given energy would be less than for a conventional linac.

Duty Factors

The time variation of the accelerated beam is a very important attribute of an accelerator. An illustration of this is provided by the history of experimentation with FM cyclotrons. As originally designed these machines had a long time variation (macrostructure) of some 0.1 ms beam on followed by some 20 ms beam off. As the result of efforts at Berkeley, CERN, and Columbia making use of subsidiary accelerating electrodes and moving targets, the macrostructure has been improved so that the external beam is now on some 50 - 80% of the time. This improvement has resulted in a very large increase in the number and types of experiments which can be performed with the present accelerators. The short time variation of the external beam (microstructure) still reflects the RF structure in a duty factor of 10 - 15%; however, stacking can produce quite a smooth microstructure on the internal beam only.

The fact that the improved macrostructure recently obtained on FM cyclotrons has resulted in such a large improvement in experiment capability is connected with the fact that the vast majority of experiments in this energy region employ counting techniques, or more recently counter-controlled spark chambers. For the best exploitation of these experimental techniques a good duty factor is essential.

For nuclear emulsions and diffusion cloud chambers the time structure of the beam is of no consequence, but the relative importance of these techniques has

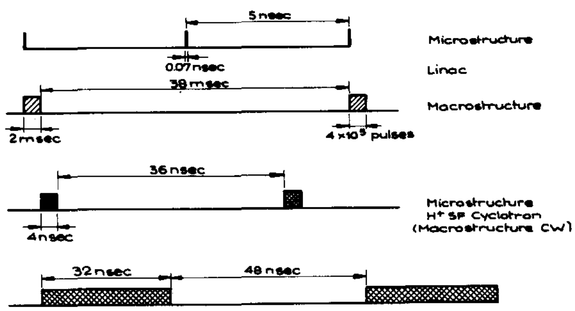

Fig. 2 Time structure for three of the possible types of meson factories.

diminished in recent years. Bubble chambers have a sensitive time of 1 - 2 ms and must be re-cycled with the beam turned off. The microstructure of the beam within the 2 ms is of no consequence. It seems clear that any of the accelerators envisaged as meson factories could provide the desired macrostructure with ease. It should be born in mind, however, that the contributions of the bubble chamber technique in meson physics have been relatively modest compared with the contributions in strange particle physics. It seems likely that this situation will not undergo any radical change.

To avoid vague generalities let us examine a typical n-fold coincidence experiment from a simple-minded point of view, where we are interested only in order-of-magnitude calculations. Let N_1, $N_2 \ldots N_n$ be the individual counting rates in each of the n counters due either to bona fide particles from the target during the beam pulse of length p or other counts indistinguishable from them on a time basis. For beam pulses of uniform size repeated ν times per second, the number of false double coincidences per second would be

$$N_{f_2} = \frac{N_1 N_2}{\nu} \, a \left(\frac{\tau}{p}\right) ,$$

$$\text{where } a \left(\frac{\tau}{p}\right) = 1, \text{ for } \tau > p$$

$$= \frac{\tau}{p}, \text{ for } \tau \ll p.$$

The number of false n-fold coincidences would be

$$N_{fn} = \frac{N_1 N_2 \ldots N_n}{\nu^{n-1}} \; a^{n-1} \left(\frac{\tau}{p}\right) .$$

where τ is the resolving time of the coincidence circuit.

Fig. 2 shows the time structure of three of the possible types of meson factories. The microstructure of the linear accelerator[8] consists of 4×10^5 pulses each of 0.07 ns length and separated by 5 ns, making up the macrostructure of 2 ms repeated every 40 ms. The microstructure of the H^+ sector-focusing cyclotron would consist of a 4 ns pulse repeated every 60 ns. The microstruture of the H^- cyclotron would consist of a 32 ns pulse repeated every 80 ns. The microstruture of both types of cyclotrons could probably be lengthened further by special effort. The macrostructure of both cyclotrons is CW.

Consider an experiment in which we are looking for a true event with a probability of one in 3×10^6 and making use of a four-fold coincidence circuit with a resolving time of 4 ns. The limiting single counting rates for which the true and false coincidences are equal, according to the above relation, are shown in Table I.

Table I

	Limiting counting rates		Time required for a ± 5% measurement (τ = 0.4 ns)
	τ = 4 ns	τ = 0.4 ns	
Linear Accelerator	6×10^4/s	6×10^4/s	28 hours
H^+ Cyclotron	9×10^4/s	9×10^5/s	1.9 hours
H^- Cyclotron	6×10^5/s	6×10^6/s	17 minutes

The limiting counting rate for the linear accelerator could not be improved unless a coincidence resolving time of better than 0.07 ns were achieved. Because of the difficulties pointed out below, such resolving times are difficult to employ in most experiments. The last column of Table I shows the time required to complete a measurement involving 1000 true coincidences.

In the foregoing discussion we have been concerned only with those counts which are completely indistinguishable on a time basis from those which are desired. We turn now to the more usual analysis which includes accidentals from background and consider the situation for different values of τ.

If resolving times of the order of 10^{-6} - 10^{-7} s are used, the microstructure of the beam is not important and we are concerned only with the macrostructure of the beam which we will describe as F pulses of length P per second. We then obtain for the number of n-fold accidental coincidences per second

$$N_{an} = \frac{N_1 N_2 \ldots N_n}{F^{n-1}} \left(\frac{\tau}{P}\right)^{n-1} .$$

Thus the ratio of $\frac{\text{singles}}{\text{accidentals}} = \frac{D^{n-1}}{N_2 \ldots N_n \tau^{n-1}}$,

where we have defined the duty factor D = FP. Thus for n-fold coincidence the ratio of signal to noise is proportional to D^{n-1}. This is a very compelling argument to make the duty factor as near to 1.0 as possible and in favour of cyclotrons over other types of accelerators.

As the resolving time of the coincidence is decreased, the microstructure of the beam becomes important. For $\tau = 5 \times 10^{-10}$ s, for example, the H^+ SFC presents a duty factor of 0.07, the H^- SFC has a duty factor of 0.4, while the linac has an effective duty factor of 0.005. The latter value arises from the fact that the effective resolving time for the linace becomes the time between pulses, which is 5 ns. The precise effective value will vary from one experiment to another, depending upon the

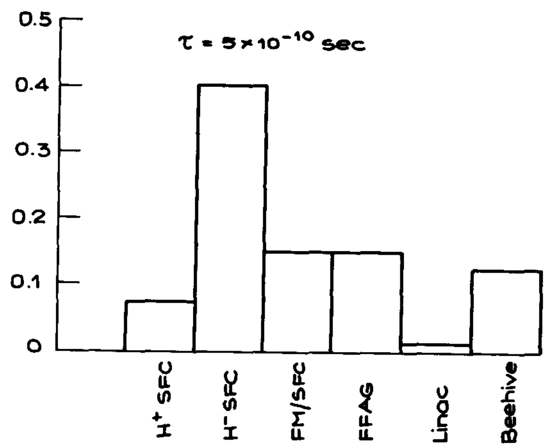

Fig. 3 Effective duty factor for external beam.

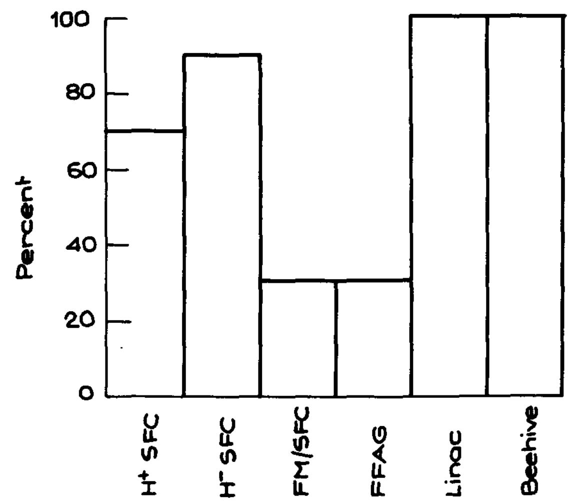

Fig. 4 Availability of beam.

time history of the wanted and unwanted pulses and whether a time selection of the sensitivity of the counters can make a useful discrimination between the two types. Factors which limit the resolving time include : a) transit time through the ounters; b) spread in velocity of the particles; and c) any decay processes which occur.

A more detailed analysis of this problem is desirable but it is already clear that the time structure of the beam is perhaps the most important criterion in the choice of a meson factory. On this basis the order of rank is as shwon in Fig. 3.

Availability of the Beam

Here we are concerned with how easily the beam can be made available for research. There has been considerable discussion of the use of internal beams in the FFAG acceleraotr and cyclotron and, in fact, a great deal of the research on pions has been done with internal targets in the FM cyclotrons. However, partly because of the problem of induced radioactivity, it seems desirable when considering the capabilities of accelerators as meson factories to place considerable weight on the availability of the beam.

The separated-orbit cyclotron shares with the conventional linear accelerator the attribute of having complete availabitlity of the beam; we will give it 100%. For the other accelerators we will obtain a qualitative estimate of availability by multiplying the percentage of beam to be extracted by a factor inversely representing the amount of design effort and development necessary (to the speaker's present knowledge) for successful extraction. The results are shown in Fig. 4.

Variable Energy

Many experiments to be done with the meson factory require the full energy beam. However there are also many experiments which would benefit from a clean beam of lower energy. The production of a high intensity beam of low-energy pions, fer example, would be optimized if a primary beam of 500 MeV protons were used. That is, the production per unit pion energy interval is optimized for low-energy pions at the lower proton energy. Similarly, for experiments concerned with the properties of the nucleus a variable energy is a very desirable feature. Most of the bio-medical research envisaged at the present time can be done best with primary protons of 500 MeV or below. This includes the production of 50 MeV negative pions for bio-medical irradiation.

Of the circular accelerators, the H^- cyclotron is the only one which has the variable energy feature without difficult complications in design.

Simultaneous Beams

Since a meson factory represents a considerable capital investment it is desirable to maximize the potential research output of the machine. This is usually done by employing a switching magnet on the external beam. Unfortunately this ruins the duty factor of the accelerator (if it is not already bad). The ideal situation would be obtained with two truly simultaneous beams of similar or differing energies, each with a high duty factor. The only accelerator either circular or linear which can satisfy this requirement is the H^- cyclotron.

Induced Radioactivity in the Accelerator

The 184 inch FM cyclotron at Berkeley operates with an internal proton beam up to 2 μA. Practically all of this beam is lost inside the machine. Although the induced activity under these conditions is a serious restriction on handling and servicing it could probably be increased by a factor of two without requiring remote handling and servicing techniques. Measurements have been made by ORNL at Berkeley and by the CERN group on the nature of the induced activity. The objective here is to determine structural materials which will minimize the induced activity. The effectiveness of this approach is still under discussion but it seems reasonable to assume that 5 μA equivalent in the 184 in. machine is a hazy line at which remote handling and servicing techniques would be necessary, or at least very desirable. Accepting this limit we arrive at the maximum values in Table II, indicating the maximum external beam which can be handled without the use of remote handling and servicing equipment.

Table II

	Limit on External Beam (Radioactivity)		Orbit diameter (assumed)
H^+ SF cyclotron	40 μA		30 ft
H^- SF cyclotron	200 μA	(700 MeV)	68 ft
	600 μA	(650 MeV)	68 ft
FM/SF cyclotron	7 μA		30 ft
FFAG ring	14 μA		60 ft
SO cyclotron	indefinite		-
Linac	indefinite		-

Development and Reliability

It is very difficult to make a quantitative estimate of how reliable an accelerator will be, or how much development effort will be required to make it reliable. The SO cyclotron and the linear accelerator suffer from being made up of a large number of small components which require a larger development effort to make them as reliable as the large single elements of a cyclotron. The record of the cyclotrons being brought into operation on time and with reliability has been particularly impressive in recent years. The two main sources of trouble requiring development have been the FM system and the extraction system. Since the H^- SF cyclotron will have neither problem it should probably be put at the head of the list : 1) H^- SF cyclotron, 2) H^+ SF cyclotron, 3) FM/SF cyclotron, 4) FFAG ring, 5) Linear accelerator, and 6) SO cyclotron.

There are some problems in the development of a linear accelerator for 700 MeV whose magnitude are unknown at the present time but which may be serious. The SO cyclotron requires a great deal of development.

Cost

The cost of an accelerator is hard to estimate. Different estimates are made on different bases andthis makes the comparison very difficult. The estimates shown in Fig. 5 refer to the accelerator alone and do not include facilities, site, buildings, shielding, experimental facilites, etc. These estimates reflect consultation and discussion with W. Brobeck but they are the responsibility of the author, with the exception of the two H^- SF cyclotrons which were estimated directly by Brobeck.

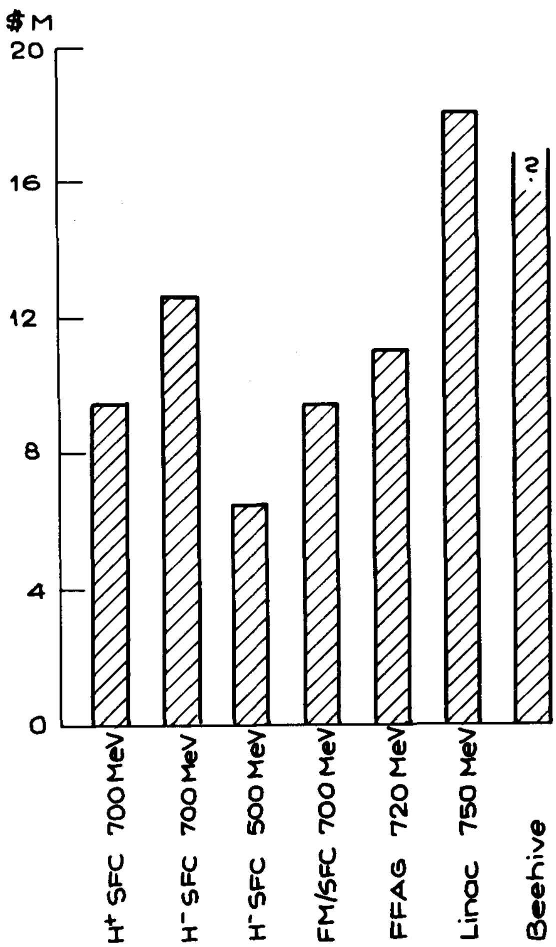

Fig. 5 Construction costs (accelerator only).

Conclusion

An attempt has been made to compare the various circular machines as meson factories and to include a comparison with the linear accelerator where appropriate. It is believed that the most important criteria have been evaluated. However there is one additional criterion which may be important, depending upon the particular laboratory involved, and that is the question of site selection. Since the experimental facilities area should be about 60,000 square feet, the difference in the area taken up by any of the circular machines is unimportant. When it comes to the conventional linear accelerator, however, the total length of the structure is over 0.4 mile; this may produce difficulties in finding a site convenient to the other facilities of the laboratory or university.

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DISCUSSION

HUGHES : I had just like to reiterate my earlier comments on the duty factor question; the microstructure is largely wiped out in most meson experiments.

TENG : In connection with Hughes' remark I think that he also pointed out that the microstructure for any accelerator with phase stability can be essentially washed out by accelerating during the last part on the unstable or defocusing RF phase. It might take some doing, but this can be done.

BLOSSER : I was a little surprised at your remarks on the relative schedules of cyclotrons and linacs. I was under the impression that the various injectors for synchrotrons had usually started up rather effectively and promptly.

RICHARDSON : We do not have here a case of copying already developed linacs; this is something which has not been built before. When you compare the first linacs of any particular model and the first cyclotrons of any particular model, the cyclotrons win hands down as far as the schedules are concerned.