MESON FACTORIES*

J. Reginald Richardson

Department of Physics, University of California, Los Angeles

Summary

Meson factories are those accelerators designed to produce beams of protons in the energy range of 400 to 1000 MeV with intensities at least 1000 times greater than those presently available from FM cyclotrons. They have an important role in future research in nuclear structure physics, elementary particle physics, and bio-medical research. The criteria for selection of a meson factory are discussed. They include duty factor and the time structure of the beam, the possibility of varying the energy of the beam, the efficiency with which a large fraction of the beam can be brought to an experimental area, the possibility of the simultaneous use of high duty factor beams of differing energy, the amount of radioactivity induced in the accelerator, and general flexibility. Additional criteria are cost and the relative difficulty of the expected technological problems. Descriptions are given of the various types of accelerators which have been seriously suggested for this role. These include the sector-focusing cyclotron for the acceleration of positive ions, the sector-focusing cyclotron for the acceleration of negative hydrogen ions, and the sector-focusing ring cyclotron. The linear accelerator for the acceleration of protons has also been suggested as a meson factory, and the final description concerns the separated orbit cyclotron, combining some of the features of the linear accelerator and the sector focusing cyclotron. An attempt is made to use the criteria in a comparison of the promise of these various types of accelerators in the role of meson factory.

Introduction

A "meson factory," for the purposes of this paper, is defined as a machine designed to accelerate proton currents of 0.07 to 7 ma to energies between 400 and 1000 MeV. It has as its prime purpose the production of fluxes of low energy pions and muons some 1000 to 10,000 times greater than the fluxes from FM cyclotrons presently operating in this energy region. Although the high energy AG synchrotrons can produce large fluxes of high energy pions (and muons) they can not compete with the meson factories in the production of low energy mesons under the clean, low background conditions essential for precise measurements.

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Energy of the Meson Factory

The fields of research which would be attacked by a meson factory if it were presently available are summarized in the following outline:

I. Nuclear Structure
- Scattering of nucleons by nuclei
- Reactions induced in nuclei by nucleons
- Pion scattering by nuclei
- Muon scattering by nuclei, including the use of polarized muons
- Nuclear absorption of pions from mesic atoms
- Nuclear reactions produced by pions

II. Elementary Particle Physics
- Muon capture-weak interactions
- Electromagnetic properties of the muon and pion
- Rare decay modes of pion and muon
- The physics of mesic atoms
- *Nucleon-nucleon scattering
- *Pion-nucleon scattering
- *Pion production
- *Neutrino interactions

III. Biological and Medical Research
- Biomedical research with protons - the radiation knife
- Biomedical effects with negative pions

For the large majority of the research fields mentioned in the above outline, (including all the experiments using stopping pions and muons), the optimum proton energy is at 500 MeV or below. For the fields marked with asterisks, on the other hand, it would be desirable to have as high an energy available as possible, although in general the yield of information is only linear with energy. Thus, one concludes that even if the design energy is as high as 800 MeV, the meson factory will spend most of its time operating near 500 MeV since that is the energy region where the meson factory is clearly superior to all competing accelerators.

It should be emphasized that an increase in beam intensity by a factor of 1000 to 10,000 over presently available accelerators would not always result in a better experimental situation unless steps are taken to prevent the experimental background from rising by the same factor. Because of this increase in intensity, we can afford to be selective in our choice of the optimum proton energy for the production of pions of any particular energy relative to the production of general background. For example, Fig. 1 shows the relative production of 150 MeV pions emerging from carbon targets of various thicknesses as a function of the energy of the proton incident on the target. Each curve is labeled in the figure with a number which represents the target thickness in MeV for the bombarding protons. The ordinate represents the yield per unit background production. Fig. 1 indicates that the optimum proton energy for the production of 150 MeV pions is about 500 MeV. Similar curves show that the optimum proton energy for the production of 50 MeV pions, from which the highest density of stopping pions and muons can be obtained, is about 450 MeV. For pions of 250 MeV, the optimum bombarding proton energy would be about 600 MeV.

The Sector-Focusing Cyclotron (SFC)

At the present time there are at least 25 SF cyclotrons either in operation, under construction, or in the planning stage. This truly isochronous cyclotron has proved to be a reliable research tool with an output beam of very high quality. The current status of this development has been covered in a previous paper of this conference.[1] The highest velocity ions which have so far been routinely accelerated in these machines corresponds to a proton energy of 50 MeV (β= 0.32) obtained at UCLA, Berkeley and Oak Ridge. In electron model studies, however, these analogue particles have been accelerated to speeds of $\beta = 0.55$ (Berkeley) and $\beta = 0.86$ (Oak Ridge). These studies, together with very extensive beam orbit calculations have given convincing evidence that there are no fundamental technical difficulties in extending the acceleration of protons in the SF cyclotron to energies in excess of 800 MeV.

Oak Ridge has proposed the construction of a meson factory in the form of a sector-focusing machine with the title of "Mc^2 Cyclotron."[2] Their studies with an electron analogue have shown that with an eight-fold azimuthal variation of the magnetic field (N=8) no adverse effects from beam orbit resonances will occur until the $\nu_r=2$ resonance is encountered at 810 MeV. At this energy the particles go through two radial oscillations with respect to the equilibrium orbit every turn. Thus if a second harmonic in the magnetic field is introduced at this point, radial oscillations will be reinforced and will grow rapidly. This will produce enough radial separation between successive turns of the protons so that the septum of a magnetic channel can be introduced to extract the beam from the cyclotron. Extraction efficiencies of some 80 percent are indicated by the experimental work on the electron analogue. A high extraction efficiency is a prime requirement for a meson factory because of the high level of radioactivity induced by any beam which is lost in the accelerator. In fact, the design value of 100-200 μa for the extracted proton beam from the Mc^2 cyclotron is assigned on the basis of the maximum induced radioactivity that one would wish to allow to build up in the cyclotron.

The high extraction efficiency quoted for this cyclotron is achieved by making use of the $\nu_r=2$ resonance as explained above, but it is not practical to move this resonance very much in energy, and so the conversion of the Mc^2 cyclotron into a truly variable energy accelerator does not seem practical at this time.

The Negative Ion Cyclotron

A sector-focusing cyclotron designed specifically for the acceleration of H^- ions has been suggested as a meson factory by the group at UCLA.[3] The over-riding advantage in the use of H^- ions lies in the fact that they can be extracted with 100 percent efficiency from the cyclotron by passing them through a very thin foil where they are stripped of their two electrons and end up as positively charged protons. As a consequence of the reversal of curvature, the protons immediately come out of the magnetic field.

The method of extraction is shown in Fig. 2 where typical positions of the stripper are shown at the various points A. Clearly a continuous variation in energy can be obtained in this way. A small bending magnet, called the combination magnet, is located where the particle trajectories for all energies intersect in a point. This magnet bends the trajectories into a single beam line and in turn provides us with a truly variable energy accelerator. The maximum energy is the maximum energy (600 MeV) of the negative ions accelerated in the cyclotron and the minimum energy is that at which the ions curve back into the cyclotron. More practically, ions whose path length is so long that the beam quality cannot be adequately preserved constitute a lower limit near 200 MeV.

The extracted beam will be dispersed by the fringing field of the cyclotron, but this dispersion can be removed by the introduction of appropriate asymmetries in subsequent achromatic bending systems[4] as shown in Fig. 2. Here M1 is the fringing field of the cyclotron and M2 is the combination magnet. Magnets M3 through M9 comprise a dispersive correction system of deflection 2α. Two examples of this system are shown in the suggested plan view of the facility in Fig. 3. The 30-degree system is for extraction into the main experimental tunnel and the 120-degree system is for Experimental Area II where higher momentum resolution is desirable for proton scattering experiments.

The extracted beam will have an energy spread due to the oscillation of particles about their equilibrium orbit with amplitude A. The energy spread of the beam $\pm\Delta E$ is given approximately by $\Delta E=\frac{dE}{dR}A$ provided this expression gives a result large compared to the energy gain per turn. Applying adiabatic damping to the results on beam quality obtained on SF cyclotrons in the 50 MeV region, we obtain an estimate for A of 2.8mm. Folding in an estimate of the effect due to the finite energy gain per turn, we obtain the following spreads in energy for the various extracted beams.

Energy MeV	Energy Spread MeV
550	± 0.82
450	± 0.73
350	± 0.68
250	± 0.53

In the case of the high resolution beam dispersionlessly extracted into Experimental Area II for proton nucleus scattering and reactions, the energy spread of the beam can be reduced from its emergent value of ± 820 kev by passing it through a wedge shaped aluminum degrader. If the wedge has an angle of 17 degrees and a maximum thickness of 0.29 inches, all the current will be passed through to the experimental areas with a full width at half maximum of 255 keV.

The negative ion cyclotron has the unique capability of furnishing simultaneously two or more beams of the same or differing energy, each with 100 percent duty factor. No other type of accelerator can do this. Fig. 3 shows one way in which use can be made of this capability. As mentioned previously in Experimental Area II is the high resolution proton beam for nuclear structure and also polarized beam scattering experiments. Experimental Area I contains facilities for high energy low intensity pion research and another area for high energy high intensity pion beams and a low energy high intensity pion area. A muon channel is provided and a bent crystal spectrometer for both mu mesic and pi mesic X-rays. Provision is made for the future addition of a separate bio-medical research area with its own extracted beam.

The special characteristics of an SF cyclotron with are necessary for the acceleration of H^- ions are the result of concern for the effects of the low binding energy of 0.755 eV for the ion's extra electron. There are two processes which may occur during the acceleration in the cyclotron which will result in the removal of this electron and the consequent loss of the ion from the beam. These are: a) scattering by residual gas in the cyclotron vacuum chamber, and b) electric dissociation by the magnetic field. The cross section for dissociation by gas scattering has been measured[5,6] and is now known with sufficient accuracy to make reliable predictions. For example, the loss in beam power due to gas scattering at an operating pressure of 10^{-7} torr is a total of 4.7 percent for the 550 MeV design.

There has been some uncertainty in the lifetime for electric dissociation, which is the result of the relativistic transformation of the magnetic field of the cyclotron into an electric field strong enough to distort the barrier of the ion so that the extra electron escapes. Since $\varepsilon=0.3\beta\gamma B$ in Mv/cm the effect increases sharply with energy. Theoretical calculations[7] on the lifetime τ of the H^- ions vs ε have yielded values differing by as much as a factor of 100 from each other, although the slopes of the curves have been very similar. Fortunately, our recent experience with the 50 MeV extracted proton beam from H^- ions in the SF cyclotron at UCLA has allowed us to put a lower limit on the lifetime for electric dissociation. The three sets of predicted lifetimes (the results of Khuri and Khoe are very similar) were used to calculate survival curves on the 50 MeV machine, where the hill fields go up to 25kG. These curves are shown on Fig. 4 in terms of the cyclotron radius. The experimental points represented by crosses are measurements obtained by comparison of the survival of H^- and H^+ ions where the only change made was the moving of the ion source and puller to symmetric but opposite positions. It is obvious that if the most pessimistic theoretical predictions were correct, no appreciable H^- beam could be accelerated to 50 MeV. We have measured the energy of the extracted beam by two methods:

1) the cross-over technique using the 9.63 MeV excited state of carbon which gives 49 MeV, and
2) the usual range-energy relation which gives 50 MeV.

These results indicate that the predictions of Hiskes should be regarded as a lower limit on the lifetime τ.

In applying these results to the meson factory we have the comparisons shown in Table I.

TABLE I

Comparison for Electric Dissociation

	Meson Cyclotron		UCLA Cyclotron
Energy MeV	550	600	50
Hill Field kG	5.27	5.45	25
Electric Field Mv/cm	1.94	2.12	2.5
Total Number of Turns	1400	1500	850
τ (Hiskes) μsec	630	80	1.6
Orbit Time on Hills, μsec	0.19		0.014
Predicted Beam Loss	2%	9%	50%

It is now clear that the criteria used in the design of the 550 MeV Pion Facility were too conservative. The electric dissociation is in fact much smaller than was assumed in that design, and considerably larger beams could be accelerated without producing excessive amounts of induced radioactivity. Using the predictions of Hiskes we find that a beam of 0.6 ma can be accelerated to any energy from 200 to 550 MeV while a beam of 0.2 ma can be accelerated to a final energy of 600 MeV.

The magnet for this design has total weight of 3800 tons of iron and 72 tons of copper, excited by 2.4 MW. The peak dee voltage is 100 kV giving an energy gain per turn of 400 keV from an rf power of 1.3 MW.

There are a number of ways in which polarized beams of protons can be produced with the negative ion cyclotron. They include: a) the elastic scattering of the external beam at small angles, and b) the acceleration of polarized protons as ordinary positive ions (this can be done because the polarized beam will never be so large as to constitute a difficult radiation problem), and c) the attachment of electrons to a beam of polarized protons and acceleration as negative ions in the cyclotron.

Because of the relatively small size of the beams of polarized protons (under [b]), the extraction problem can be handled in a straightforward manner. The separation between turns n near the final orbit of radius, 330 inches, is 0.07 inch at an energy gain per turn of 400 keV. The use of a magnetic channel of the Oak Ridge type, since it can produce a reverse field of 4000 gauss, would reverse the curvature of the positive ions if it were placed in one of the valleys where the field is 2000 gauss. Thus, if the main magnetic field of the cyclotron were reversed for the operation with positive polarized ions, the resulting trajectory would be similar to that followed by a stripped negative ion. The power consumption in such a channel would be about 300 kW. On the basis of analogous operation at lower energies, extraction efficiencies of the order of 50 percent would be expected.

In this way, with an injection efficiency of 12 percent and an extraction efficiency of 50 per cent, one would expect to get 6 percent of the source output in the final beam. If a polarized source of 2×10^{12} polarized protons per second can be developed, it would give some 1.2×10^{11} protons per second in the final beam. This is to be compared with the expected overall efficiency in the linac of 1.2 percent (100 ma injected to give 1.2 ma time average) which would yield an output beam of 2.4×10^{10} protons per second from the linac.

The Ring Cyclotron

This is a concept which has been pursued intensively by a group at the ETH, Zurich, Switzerland. A plan view of this design is shown in Fig. 5. One sees that in essence it is a large SF cyclotron with the central region cut out and placed over to one side as an injector cyclotron. By operating this central region at a higher characteristic magnetic field it ends up considerably smaller in diameter than is the region cut out of the main magnet. The injector cyclotron will be a 4-sector spiral machine with output of 68 MeV protons at a final orbit radius of 110 cm. These protons can be used for experimental research at this energy or they can be injected into the big ring where they will be accelerated to a final energy of 510 MeV. The initial orbit radius in the ring is 200 cm and the final orbit radius is 440 cm, while the overall diameter of the magnet is 43 feet. The ring magnet is made up of eight independent sectors, and has a total weight of about 1600 tons of iron and 60 tons of copper, and requires some 500 KW of exciting power. The accelerating system consists of 4 rectangular TE cavities at 50 Mc giving an electric field of 300 kV and thus furnishing an energy gain of some 1 MeV per turn. Four inter-sector spaces are left free for injection, extraction, etc.

The relatively large energy gain per turn corresponds to a radial displacement of 4mm for successive turns near the final orbit radius. It is hoped to use the $\nu_r = {}^3{}_2$ imperfection resonance to increase this turn separation so that the septum of an extraction channel can be inserted between turns. Beam dynamics calculations are being pursued to optimize the parameters, and it is believed that an extraction efficiency equal to the 80 percent achieved on analogue II (ν_r=2) at Oak Ridge is achievable. Although the figure shows the possibility of meson production from an internal target, it is realized that this is impractical for beams larger than 10 μa because of the intense residual radioactivity resulting from such bombardments. An interesting feature of the design is the working path on the ν_r, ν_z plane, where ν_r increases from 1.0 to 1.5 while ν_z is maintained above 0.7. This is in contrast to the situation in the ordinary SF cyclotron where ν_z starts near zero, increases to about 0.3, and remains constant thereafter.

The Swiss project has received preliminary approval and in undoubtedly the furthest advanced of any of the meson factory projects. A considerable amount of model work has been done. A model in scale 1:5 of a magnet sector has been built and studied, and a full scale RF cavity has been built and is being tested. Also, a site for the laboratory has been selected and acquired by the Swiss Federal Government.

Linear Accelerator

In the linear accelerator it is easy to show that unless charge carried on foils or grids is put into the volume of the beam, first-order radial stability is incompatible with longitudinal phase stability. A way of circumventing this difficulty is provided by the strong focusing principle, so that quadrupole magnets are used, focusing in the x direction (say), defocusing in y, followed by a magnet defocusing in x, focusing in y.

A linac for meson production must first accelerate protons in the non-relativistic region. Here drift tubes are used to provide the rapid change in phase velocity required to match the changing particle velocity and to provide field-free drift spaces for the particles during the time that the field is reversed. Later there must be a transition to the relativistic region where an iris loaded wave guide can provide the more nearly constant phase velocity required. The Yale group,[8] having made an extensive design study on the linac, has proposed a 0.75 MeV Cockcroft-Walton injecting into a 200 Mc drift tube tank. A conventional 2π -mode drift tube structure accelerates the protons to 190 MeV (β=0.56) through six independent cavities. Nearly 200 magnets (for radial focusing as mentioned above) in 261 drift tubes are required in this part of the linac. A typical drift tube, with enclosed quadrupole magnet, is shown in Fig. 6.

The efficiency of the drift tube form of the accelerator, i.e., the power put into the beam compared to the total radio-frequency power required, falls off very rapidly as the particle velocity approaches that of light ($\beta \to 1$). Economy therefore dictates a transition to the loaded wave guide type of linac at or below an energy of 200 MeV (β=0.57). Again for reasons of economy, it is necessary to increase the operating frequency from 200 to 800 Mc in the relativistic section of the linac. A typical two-cavity subsection of the iris-loaded wave guide part of the accelerator is shown in Fig. 7. There are 71 such sub-sections in the relativistic section with 70 quadrupole magnets as shown.

In electron linacs, the travelling wave mode is used, since β=1 and the electrons maintain the correct phase relative to the rf power regardless of the magnitude of the electric field. For protons, however, this is not true and the effect of the beam loading is to lower the field, which in turn decreases the output energy of the linac and results in a spread of output energy with time during the pulse. In addition there will be beam loss due to loss of phase, and in fact there will be only one magnitude of beam current at which the field distribution is correct for acceleration.

To accelerate protons in the relativistic section one is thus forced to the standing wave mode where beam loading will reduce the field level, but should leave the distribution unchanged. Thus one can hope that compensation may be supplied by measuring the field level at some point in the cavity and applying during the pulse, a correction which increases the power output of the amplifier. In a long, loosely coupled standing wave structure, it will be necessary to check the detailed constancy of the field distribution. Unfortunately, the narrow bandwidth presents real problems in the standing wave case, and therefore considerable effort has been made to optimize the structure in the loaded wave guide. For standing wave structures, it is believed that the π mode (in which successive cavities between the iris electrodes have opposite field directions at a given time) has the highest shunt impedance. This mode nominally has equal field amplitudes in all the cells, but resonant frequency errors in individual cells will perturb these amplitudes, and in order to flatten the tank (adjust all cell amplitudes to equality) the frequency of each cell must be adjusted.

The iris diaphragms shown in Fig. 7 are conventional discs with holes in them and give borderline band widths of 2 percent. By cutting four 50 degree radial slots in the discs, however, the Yale group has succeeded in boosting the band width to an apparently safe 7 percent. The Los Alamos group,[9] on the other hand, have concentrated their work on the cloverleaf structure of wave-guide and are proposing its use, although otherwise they have ended up with a design which is virtually identical with that of Yale. The cloverleaf is shown in Fig. 8 and consists of slotted irises with the cloverleaf form of the cavity between the irises designed to produce radial components of the magnetic field formed in the TM_{010} mode of a cylindrical resonator. These radial components couple through the slots from cell to cell and thus give close coupling and a relatively large band width with high shunt impedance. Whether or not the improved performance of the cloverleaf is sufficiently important to justify the undoubted increased cost and complexity is still unresolved.

In Table II are shown the parameters of the linacs suggested by Yale and Los Alamos. In the Yale design the protons are injected at 0.75 MeV into a drift tube cavity 5 meters long. This is followed by five cavities of the same type, each 25m. long, at which point the protons have an energy of 190 MeV. Transition is now made to an iris-loaded waveguide which consists of 142 cavities each 2.5m. long. The total RF instantaneous power level for the sum of the two types of structures would be 96 MW. This is prohibitive both from the point of view of expense (RF power is much more expensive than ordinary power) but also the technology required to build a structure that will withstand this magnitude of power density is not available. Thus a pulse technique must be used to reduce the average power consumption (and heating) to a more reasonable value. A pulse length of 2 milliseconds repeated 30 times per second gives a macrostructure duty factor of 6 percent and an average RF power of 6.1 MW.

The low duty factor of the linac is a desirable feature in its application as an injector for a synchrotron, but it is a serious disadvantage in its use as a meson factory. Various suggestions have been made to increase the duty factor of the linac, the most far-reaching being the use of storage rings to store the beam from the linac and then dribble it out over a long period of time. Unfortunately, although single-turn extraction from a storage ring may be made very efficient, slow extraction of the beam usually involves losses either in beam quality or in actual physical loss of the beam with the concomitant problems of very high induced radioactivity.

The normal time structure of the linac is shown in Fig. 12. The reasons for the macrostructure are discussed above. The peculiar microstructure arises from the necessity of changing the frequency from 200 Mc to 800 Mc at the transition point near 200 MeV. Thus only one in four of the cycles at the latter frequency is occupied by particles. In order to have a reasonable tolerance for the transition, and because of adiabatic damping of the synchrotron oscillations, the bunching may be worse than that indicated.

There seems to be no hope for improvement of the macrostructure duty factor of the linac beam. Difference in path lengths would have to be impractically large in order to spread the beam in time and smear out the macrostructure.

For the microstructure, however, it appears that the poor duty factor can be improved at the expense of worsening the energy spread of the beam. The phase spread can be increased by adding some noise to the tank phase and voltage controls, so that the pulse width is increased from 0.2ns to 0.4ns. However, this will lead to an energy spread of ±7 MeV, making the requirements of the beam transport system much more severe. Another technique, which can be used for output proton beams of energy over 100 MeV less than the maximum proton energy, is to shift the RF to the phase unstable side in two cells of the 800 Mc section of the linac and to turn off the RF to all subsequent cells. In this way an energy dispersion is provided which is larger for the particles near the synchronous angle than for the others and so the beam tends to spread out in time as it drifts through the unexcited cells of the linac. Of course, it is necessary to accept a spread in energy with this technique, in particular a spread of ±25 MeV at 650-700 MeV, ±10 MeV at 550-600 MeV, and ±5 MeV at 450-500 MeV. Another method of spreading out the microstructure of the beam, suggested by the Yale group, is to bend the beam through 45 degrees clockwise (say) in a strong field gradient then through 90 degrees counterclockwise in a uniform field and finally through 45 degrees clockwise in a strong field gradient. By this means a finite lateral spread of the beam is transformed into a finite spread in time and similarly variations in the space density will be reflected as variations in the time density of the beam. A beam path length of some 75 feet is required to spread the beam over a time of one cycle.

Separated Orbit Cyclotron (SOC)

The Oak Ridge group[10 11 12] has taken the original "beehive" concept of F. M. Russell and flattened it into a single plane by increasing the energy gain per turn until they have achieved a minimum turn spacing of 5 inches. In this way the orbit becomes a flat spiral and the magnets are simpler and take much less power. A plan view of part of such an accelerator is shown in Fig. 9. The shape of the sector magnets is determined by the specification of a mean field in the sector of 7000 gauss and the requirement that the azimuthally averaged field increase with the total energy as $\overline{B}=\gamma B_o$. The rectangular cavities shown in the figure are schematic. Actually an azimuthally directed electric field which increases with radius would be desirable in order to increase the minimum separation between turns, and some progress in modelling such cavities has been made. The simplest cavity meeting the basic requirements would be rectangular and would operate in the TM_{110} mode. This gives a sinusoidal variation of peak electric field with radius, but by exciting other $TM\mu 10$ modes it has been found possible to move the maximum in the peak field to the region of outer radii.

The usual cyclotron isochronism condition can be written

$$\omega = \frac{\omega_{rf}}{n} = \frac{e\overline{B}}{\gamma m_o c} = \frac{eB_o}{m_o c}$$

where n is the harmonic number. The phase of each cavity must be adjusted so that the synchronous particle crosses the gap at the phase stable angle about 30 degrees before the rf reaches a maximum.

For the final section of an 800 MeV SOC, an energy gain of 25-30 MeV per turn will give the desired turn separation. This would be furnished by some 30 cavities operating at 50 Mc with a maximum electric field of 10 kv/cm. The rf power required for a given SOC varies as the square of the orbit spacing, if the other parameters are held fixed.

In the configuration proposed by the Oak Ridge group the alternating gradient pole tips of a given sector are all driven from a common yoke structure by a common pair of coils. The magnitude of the field gradient is maintained constant throughout the machine, having a value of about 1 to 1-1/2 kgauss/cm. Fig. 10 shows a cross-section of four pole pairs with their associated beam tubes of 1-1/2 inch diameter and with field shaping shims. This back to back arrangement of the poles is essential for minimum orbit spacing, but it can obviously only be used if there is an odd number of magnet sectors in one turn. However, there is an important reason why one would like to have the successive turns of the magnet with similarly directed gradient rather than the opposing situation shown in Fig. 10. This is due to the fact that if one magnet sector contains a full magnet period, the transverse betatron oscillation frequencies ν_r and ν_z will be twice as great as for the case where two magnet sectors are required for a full magnet period. A simple example of the latter situation obtains when each sector contains either a focusing (+) or defocusing (-) lens in alternating succession. Another example is where a triplet (+-+) is followed by one of the opposite kind (-+-). However, if each sector forms an identical doublet (+-) we have reduced the length of the magnet period by a factor of two and have thus increased ν_r and ν_z by the same factor. This change clearly increases the acceptance of the accelerator and improves the tolerance situation on magnet placement, etc. It appears likely that with the use of shims similar to those shown in Fig. 10, similarly oriented gradients can be used without much increase in the minimum distance between turns.

The reverse curvature 90 degree arc shown in one sector of Fig. 9 shows the suggested method of variable energy extraction from the SOC. In the deflection sector there is a drift space somewhat longer than that of a normal sector. This upsets the periodicity of the structure and therefore requires special treatment in its beam dynamics. The magnet sectors immediately preceding and succeeding the deflection drift space can be treated as part of a beam matching system similar to the situation obtaining at injection from a linac into an AG synchrotron.[13] The configurations and gradients of the magnets must be chosen to make the two beam areas match in phase space. The Oak

Ridge group has shown that matching of at least 99 percent can be obtained.

The magnetic field in the movable extraction magnet would be about 18,000 gauss and would bring the various energies into the same extracted beam line.

Because the protons only pass once through the magnetic field of the SOC, coherent perturbations leading to instability through resonances are not important. In fact, the error analysis used in linear accelerators, aside from some radial effects, is almost directly applicable to the case of the SOC. The results of an analysis [11] applied to the 800 MeV SOC indicate that the worst error in the magnet is non-collinearity caused by a displacement Δ of the center magnet of a triplet relative to the end magnets. In calculating the required tolerances one can include the damping of the transverse motions, but also one must take account of the coupling between the radial and longitudinal motion, which will require some 3mm of space per 10 degrees of phase oscillation. The result for a 1.5 inch aperture and an input beam quality of 10mm mrad is a tolerance on Δ of 1 mil which requires a bench alignment of the poles to 1 mil, r.m.s. The relative alignment of the assembled lenses, however, is less stringent, being some 5-10 mils, r.m.s. In common with most accelerators, it is found that the long length tolerances for the SOC are very relaxed.

One can write the azimuthally averaged radius of the particle in the SOC as $\bar{\rho} = \frac{n\beta c}{\omega_{rf}}$ and then one obtains for the radial interval between turns

$$\delta\bar{\rho} = \frac{n^2\Delta E}{m_o c\beta\gamma^3\omega_{rf}}$$

where ΔE is the energy gain per traversal of a cavity. It is clear from this relation that $\delta\bar{\rho}$ varies a great deal with energy, so that a single SOC will not be very efficient in accelerating particles all the way from low energies to high energies. Since the physical limitation on $\delta\bar{\rho}$ seems to be 4-5 in. for a flat spiral, it is desirable from the point of view of economy to have at least three separate rings in an 800 MeV accelerator. The number of cavities will increase as one goes to the larger rings in accordance with the above relation. A conceptual design showing four rings is shown in Fig. 11 and the corresponding numerical values are shown in Table III. The total magnet power required is 1.2 MW to excite 125 tons of copper.

Note that the exciting rf power of the total accelerator is about 9 MW in contrast to nearly 100 MW for a linear accelerator of similar energy. It is this contrast which allows the SOC to be run continuously with a 100 percent macrostructure duty factor compared to 5 or 6 percent for the linac. The reason for the factor of 10 greater efficiency in the use of rf power by the SOC is the multiple use of the cavities in accelerating the beam. For example, each of the cavities is used about 20 times in the big ring. For average currents of the order of an ampere, of course, the difference would be unimportant, but for presently discussed current goals, the difference appears to be crucial. Table III shows that the increase in output from 1 ma to 5 ma would be comparatively inexpensive in the case of the SOC.

It should be pointed out that the energy of the SOC can be increased by building additional ring stages as desired. It is interesting to consider the scaling laws under the assumption that the rf frequency and energy gain per gap is kept the same and that the additional spiral is flat with the same minimum $\delta\bar{\rho}$. Then $\frac{n^2}{\beta_m\gamma_m{}^3}$ = constant where β_m and γ_m are the maximum values of the velocity and the total energy. Thus one finds that an additional ring to increase the energy to 1250 MeV would require a magnet about 25 percent heavier than Stage 3, and it would also require some 60 percent more cavities and rf power than the Stage 3 of Table III.

TABLE II

Suggested Linac Parameters

	Yale	Los Alamos
Maximum Energy	753 MeV	792 MeV
Average Current	1.2 ma	1.0 ma
Duty Factor (macrostructure)	6%	6%
Duty Factor (microstructure)	4%	4%
Frequency of non-relativistic section	200 Mc	200 Mc
Frequency of relativistic section	800 Mc	800 Mc
Energy of transition	190 MeV	175 MeV
Peak RF power (relativistic section)	76 MW	46 MW
Peak RF power (non-relativistic section)	19 MW	17 MW
Total peak RF Power	95 MW	63 MW
Average RF Power (both sections)	6.1 MW	3.8 MW
Injection Energy	0.75 MeV	0.75 MeV
Pulse Repetition Rate	30 pps	30 pps
Overall length of Relativistic section	453 m	575 m
Total length	2000 ft.	2400 ft.

TABLE III

800-MeV Separated Orbit Cyclotron

Stage	1	2	3	Total
Energy Span, MeV	0-100	100-350	350-800	0-800
RF Power, megawatts	1.8	3.5	4.8	10.1
Steel Weight, tons	980	2300	4200	7480
Inner Radius, feet	8.4	17.8	45.8	
Outer Radius, feet	17.8	28.3	56.3	
Cost, million $				
1 mA	6.2	7.1	12.5	25.8
5 mA	6.4	7.5	13.2	27.1

Duty Factor

The time structure of the beam from the various accelerators is shown in Fig. 12. The structure of the SOC beam will be governed by the synchronous phase and the design frequency. At 50 Mc the beam would consist of a burst 3nsec in width every 20 ns, similar to the H^+ SF cyclotron and would also be CW in macrostructure. The most difficult microstructure to work with for counting and spark chamber experiments is the linac, but we have mentioned above several schemes which have been suggested for alleviating the difficulty, most of which unfortunately increase the energy spread. However, this problem seems solvable in the long run. On the other hand, it also seems to be true that any of the accelerators can be arranged to give a short, sharp pulse for time of flight experiments--for the cyclotrons this is feasible because of the planned axial injection from an internal source.

The macrostructure duty factor, however, is a different story and there seems to be no way of removing the disadvantage of the 6 percent macrostructure duty factor of the linacs. The effect of this duty factor on the research potential of a meson factory has been explored.[14]

It is clear that the ratio of true coincidences to accidental coincidences (signal to noise) in an n fold system is proportional to D^{n-1} so that one would like to have the duty factor D as close to unity as possible. The quoted reference compares the minimum cross sections that can be investigated by two accelerators in the time of one day, one of the accelerators having a duty factor of 5 percent and the other having a duty factor of 100 percent. They conclude that for a "discovery" experiment (low precision) the high duty factor machine can explore down to $2 \times 10^{-36} cm^2$ while the low duty machine can only get to $4 \times 10^{-35} cm^2$. Similarly, a precision measurement can be made by the high duty machine on cross sections as low as $2 \times 10^{-33} cm^2$ in one day while for the low duty factor machine 20 days would be required for the same precision.

It is difficult to overemphasize the importance of duty factor in this energy region. The experience at the synchrocyclotrons has been that the increase in macrostructure duty factor effected in recent years has made possible a large number of experiments which were not feasible before. To quote from a paper on "Radiative Muon Capture in Ca^{40}"[15], the 600 MeV CERN synchrocyclotron "gave a duty cycle of 50% in comparison with the value of 2% which characterizes the normal operation of such accelerators. This great increase in the duty cycle reduced the accidental coincidence rate to a level which made the experiment feasible, although large corrections still had to be made for accidental events." Several other papers from FM cyclotron laboratories have emphasized the same point.

Variable Energy

Because the optimum proton energy is different for different experiments, it is important that the accelerator be able to furnish beams of varying energy. The negative ion cyclotron can produce a beam which is continuously variable in energy. The linac, by turning off cavities, can produce discrete jumps in energy of about 10 MeV, while the SOC, by extraction at successive turns, can produce discrete energy jumps of about 25 MeV. The Mc^2 cyclotron cannot give a variable energy, and this may be its most serious liability.

Simultaneous Multiple Beams

The output of most modern accelerators leads to one or more switching magnets, where the beam can be switched from one experimental area to the other. However, no more than one experimental area at a time can be furnished with a beam of 100 percent duty factor. The only exception to this rule among the candidates for the role of meson factory is the negative ion cyclotron. In this machine, two strippers can be placed at the same or differing energies so that two or more simultaneous beams can be extracted at different azimuths, each with a duty factor of 100 percent. Where the capital investment in the project is as large as it will be for a meson factory, this is an important capability in making the maximum possible use of the accelerator.

Induced Radioactivity

The beam of a meson factory can induce radioactivity to the extent of 100 to 1000 times that induced by the 2μa lost in the 184 inch cyclotron at Berkeley. The objective of the design is to concentrate the induced radioactivity in the targets and beam dumps, and keep the activity in the accelerator to a level well below that requiring remote handling apparatus. The cyclotron designs have conformed to this objective by keeping the radiation level in the machine to some two or three times that presently obtaining in the 184 inch cyclotron. In the case of the linac, the induced activity should remain fairly low except in the transition region between the 200 Mc and 800 Mc sections. There may be considerable loss of beam at this point, at least initially, because there still appear to be some problems in this region. Failure of one of the quadrupole focusing magnets will spray the beam in the linac and so there must be a safety device that turns off the beam in this event. The same consideration applies to one of the magnets in the SOC.

Conclusion

The table "Comparison of Meson Factories" summarizes the present position on these accelerators. The average current from the H^- cyclotron assumes an injection efficiency of 12 percent for the Ehlers 5 ma source[16] which is not far different from the efficiency already attained on the

TABLE IV

Comparison of Meson Factories

	H^+ Cyclotron	H^- Cyclotron	Ring Cyclotron	Linac	Sep. Orbit Cyclotron
Energy (MeV)	810	600	510	750	800
Energy Variable MeV	No	200-600	No	200-750	375-800
Duty Factor Macrostructure	100%	100%	100%	6%	100%
Average Current (mA)	0.2	0.6*	0.08	1.2	5
Average RF Power (MW)	0.9	1.3	--	6.1	15
Overall Size of Accelerator (feet)	70 diam.	70 diam.	43 diam.	2000 x 17	360 x 180
Polarized Protons** per second	1.8×10^{11}	1.2×10^{11}	--	2.4×10^{10}	4×10^{11}
Simultaneous Multiple Beams	No	Yes	No	No	No
Cost of Accelerator (Millions of dollars)	10.4	6.6	7.0	20.0	27.1
Cost of Project	39.7	19.8	--	55.0	65

* Current rating 0.6 mA from 200-550 MeV and 0.2 mA at 600 MeV.
**For comparison purposes, a polarized source strength of 2×10^{12} protons per sec. is (optimistically) assumed in each case.

small Birmingham SF cyclotron. The estimates of the polarized proton beam are made on the basis of the same (optimistic) polarized source strength of 2×10^{12} protons per sec. The costs of the accelerators do not include engineering, but this appears to be a fairly uniform percentage in the various estimates. The costs of the projects include the accelerator, building, shielding, engineering, beam handling equipment and some contingency. In order to make a fair comparison, escalation is not included. The costs of a 1 ma version of the SOC would be for the accelerator, $26 million and for the project, $58.5 million.

It is clear that any or all of these machines are technically feasible. From the user's point of view, however, because of the duty factor problem, the linear accelerator at 1 mA cannot compete with even the smallest of the other machines in those experiments involving low energy and stopping pions and muons, on which rests the primary justification of the meson factory. The lesson of the history of the synchrocyclotron is very clear in this respect. Now the research program of the meson factory justifies the construction of several such machines. However, if only one of these machines is to be built, it should not be a linear accelerator.

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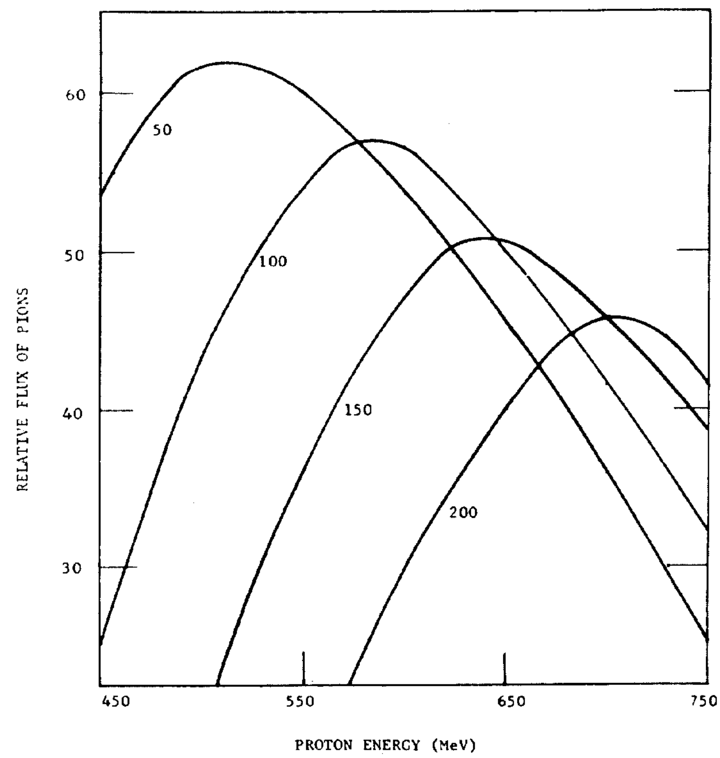

Fig. 1 Flux of 150 Mev π^+ as a function of bombarding proton energy. Different target thicknesses are normalized to the same background.

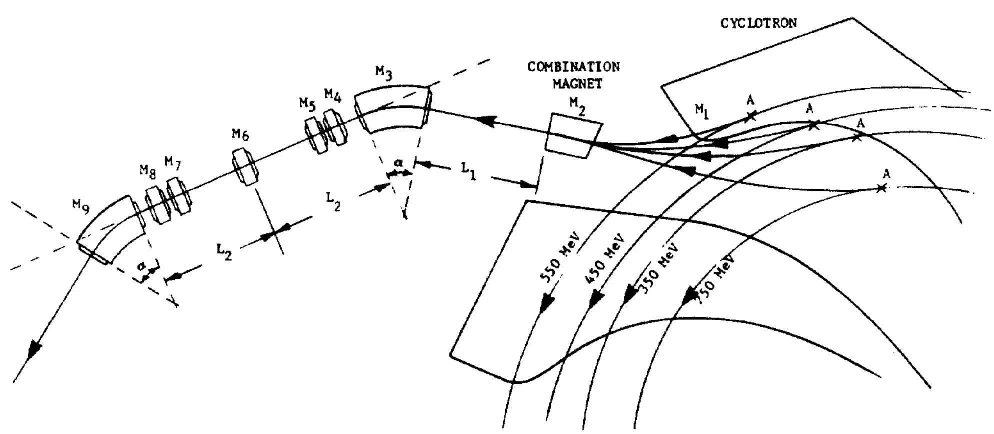

Fig. 2 Stripper positions (A) for the extraction of H^- beams of various energies into a dispersionless extraction system.

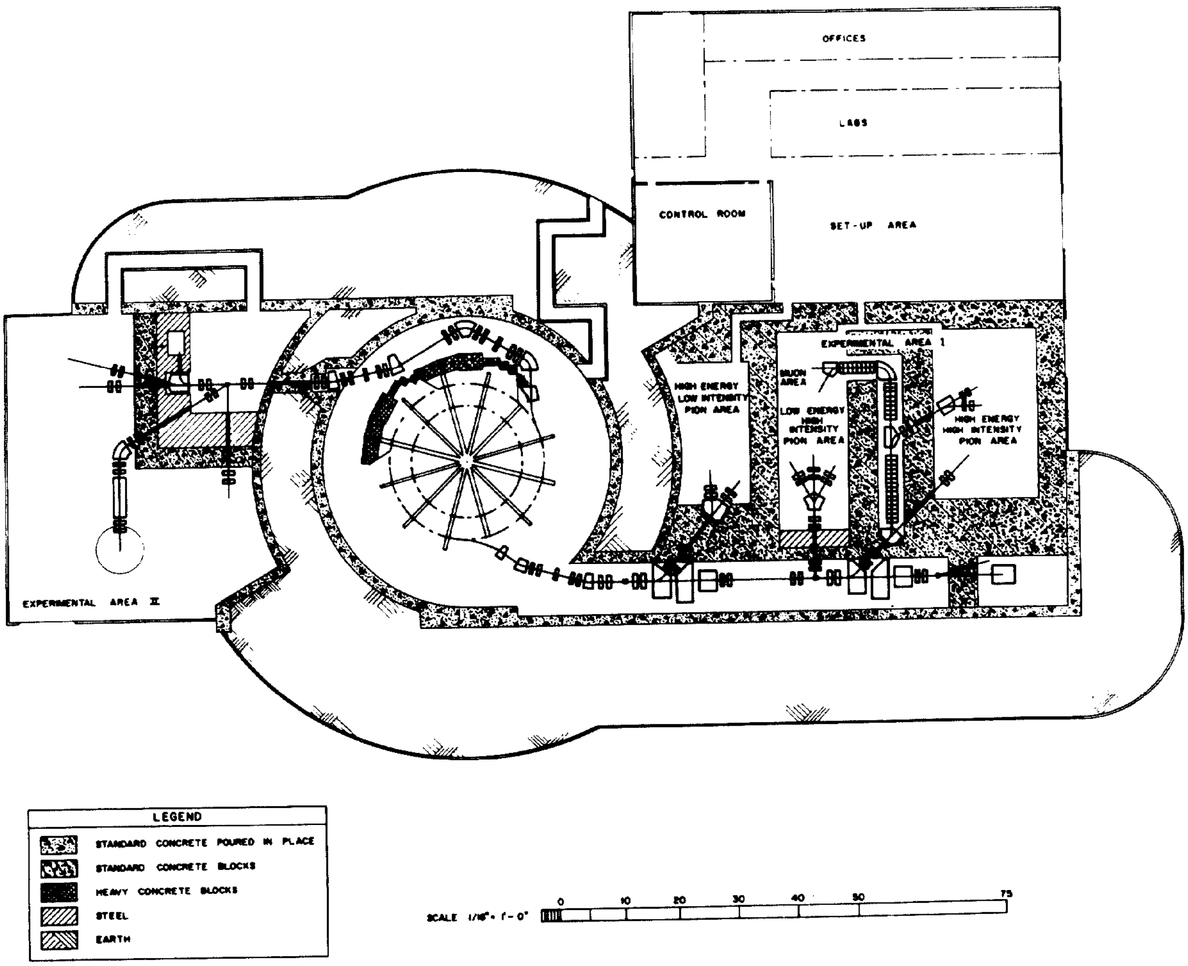

Fig. 3 Plan view of H^- cyclotron facility.

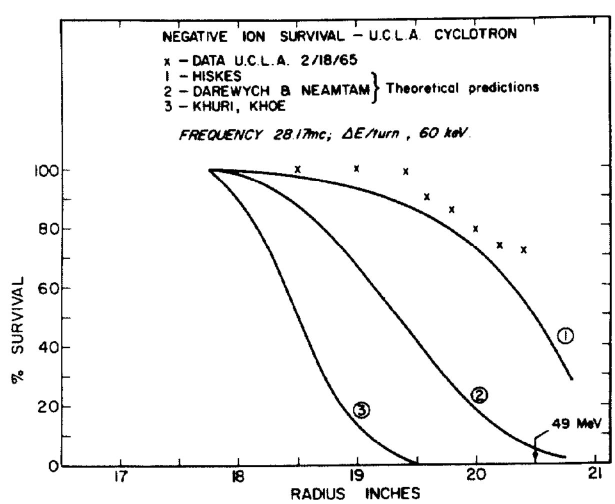

Fig. 4 Theoretical survival curves for H^- ions and the experimental data for the UCLA cyclotron.

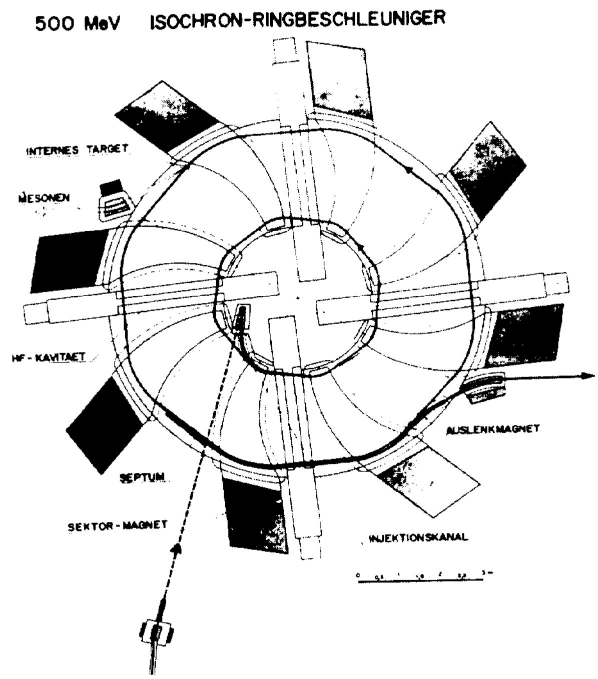

Fig. 5 Plan view of ring cyclotron proposed by ETH, Zurich.

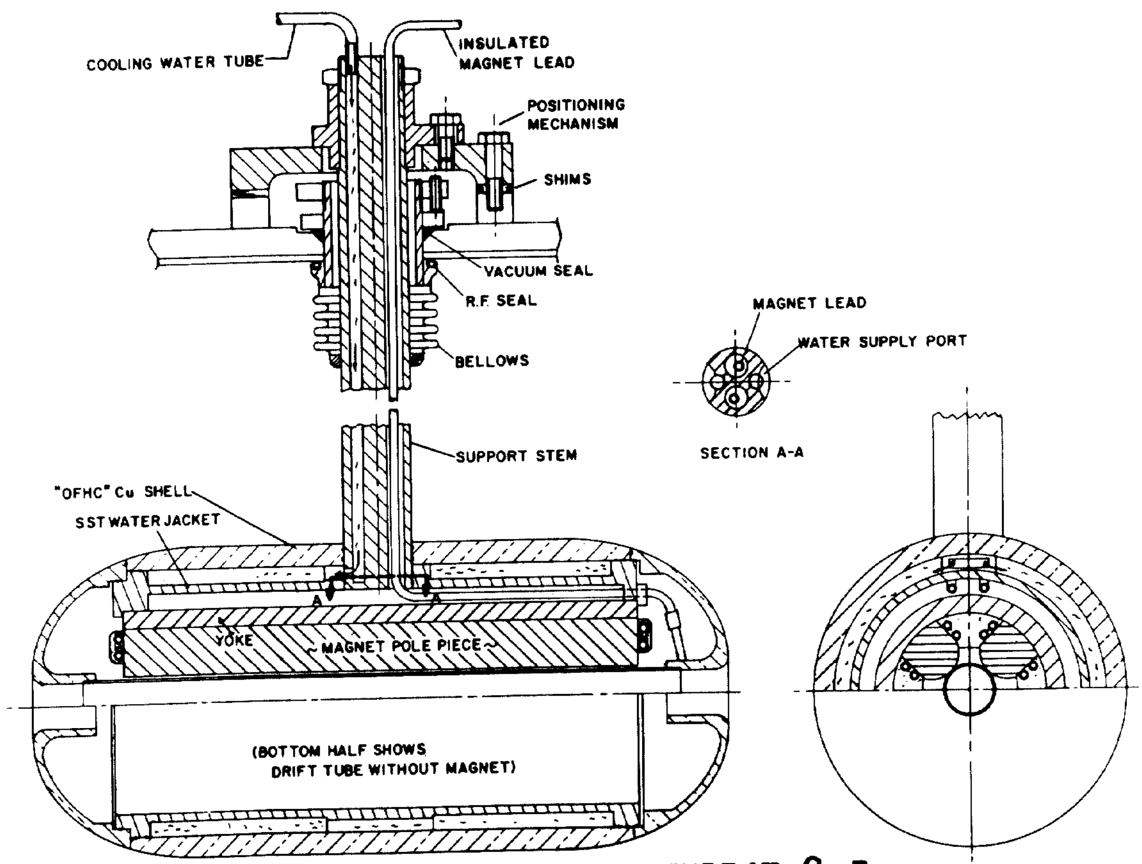

Fig. 6 A drift tube in the Yale linac design at β = 0.3. 261 of these are required.

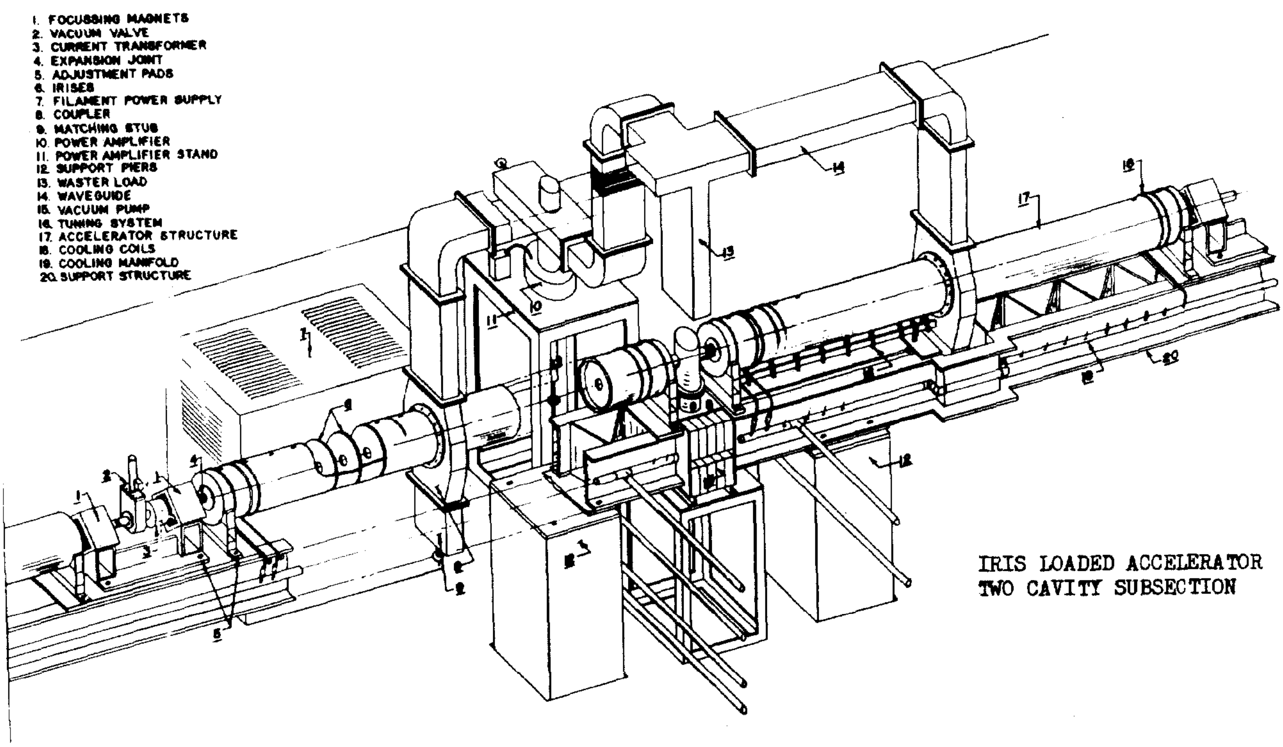

Fig. 7 Typical two-cavity sub-section of relativistic section of Yale design. 142 cavities are required.

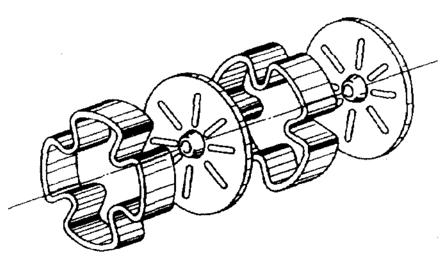

Fig. 8 Cloverleaf structure suggested by Los Alamos for the relativistic section of the linac.

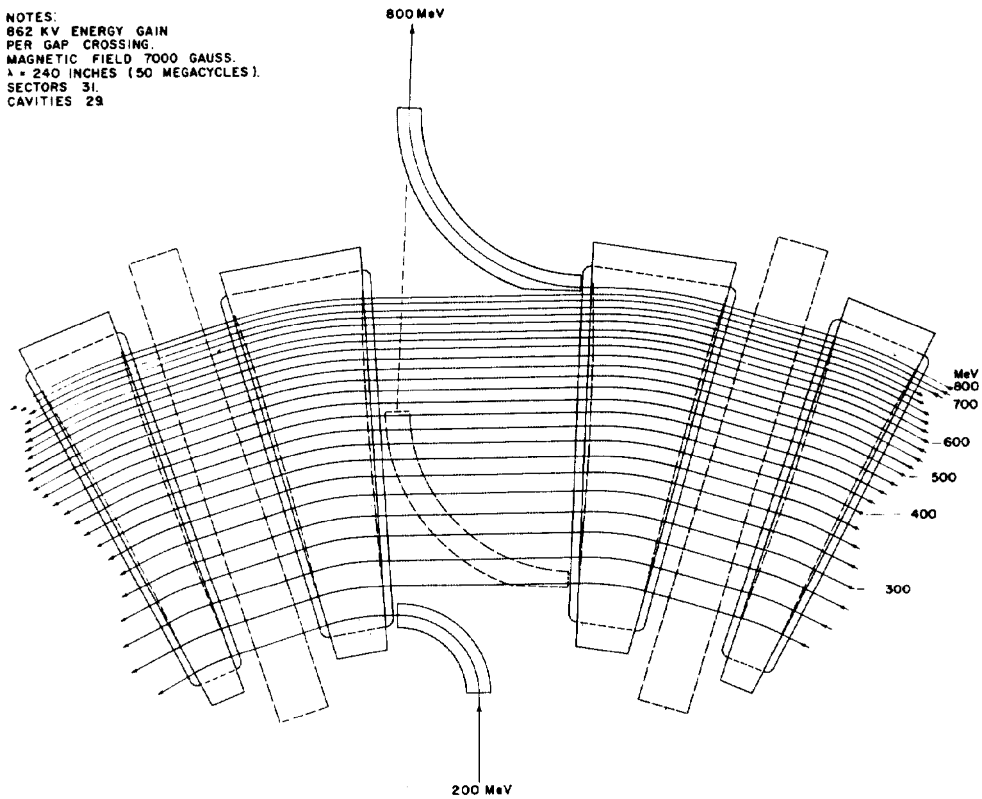

Fig. 9 Plan view of the spiral orbits in the SOC.

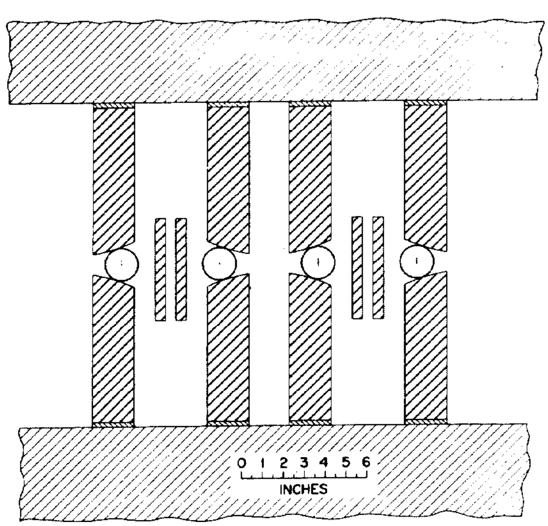

Fig. 10 Four pole pairs and associated beam tubes in the SOC.

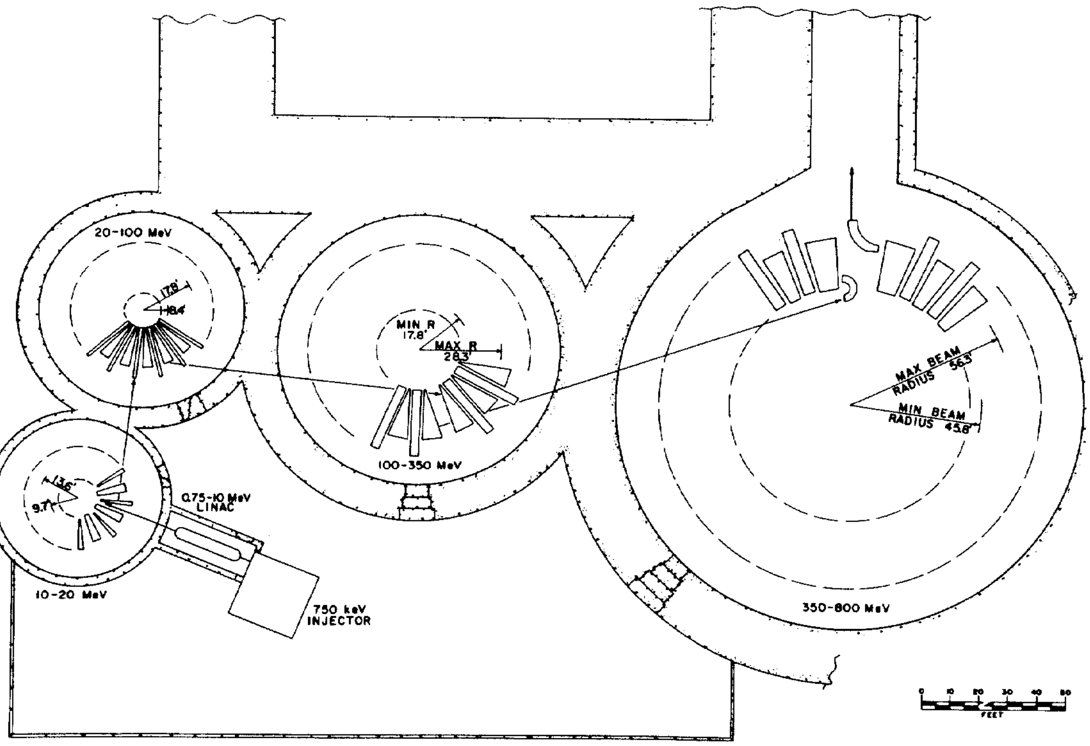

Fig. 11 Conceptual design of an 800 Mev SOC.

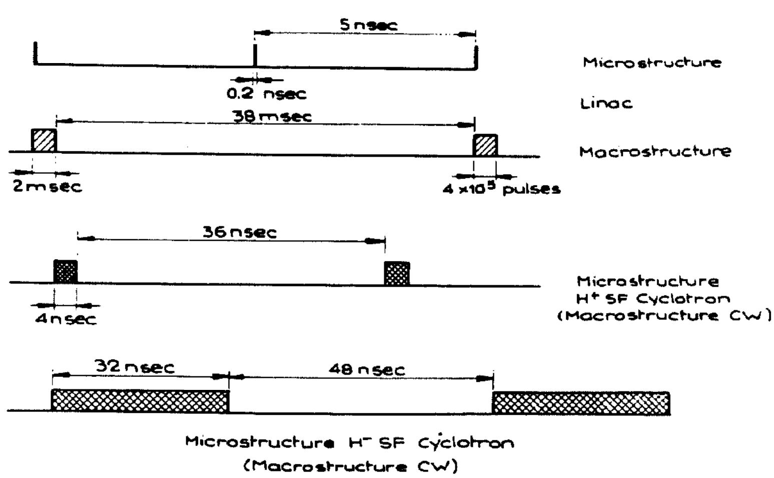

Fig. 12 Comparison of the time structure of the different meson factories.