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PROGRESS REPORT ON THE 500 MeV ISOCHRONOUS CYCLOTRON MESON FACTORY OF ETH ZURICH

Invited Paper

by J.P. Blaser and H.A. Willax

Abstract

The goal is a continous external proton beam of the order of 100 μA, the usable current depending mainly on extraction rate because of activation. The energy of 500 MeV is best suited to produce high fluxes of low energy or stopped mesons. The main fields of the research are planned to be: properties and interactions of mesons and nucleons, nuclear structure physics and medical and biological applications. The use of internal targets in field free regions as well as external targets should provide a great variety of beams for simultaneous experiments. The two-stage accelerator has a 70 MeV sector focussed cyclotron for injection into an isochronous ring accelerator consisting of eight spiral sector magnets. Four cavities operating at 50 MHz should provide at least 1 MeV energy gain per turn. In the course of present development the main fields of work are orbit dynamics and measurement on 1:5 scale magnets and design of a 1:1 model magnet sector. v_z is to be kept around 0.95 throughout acceleration and $v_r = 1.5$ may be used for resonance extraction. Experiments to reach high gap voltage on a full scale cavity in vacuum are in progress (200-300 kV obtained at present). Remaining problems are some aspects of mechanical structure, in particular the vacuum chamber and schemes for quantitative extraction and secondary beam production from external targets at very high radioactivity levels. Funds of 21 Million Dollars have been approved for construction of accelerator and buildings. A building time of 5 to 6 years is expected if development can continue in favorable conditions.

1. Aim of the Project

The accelerator shall equip a new research center operated on a national scale. Main research shall be in the fields of elementary particle physics, nuclear structure physics as well as technical and especially medical and biological applications. It will enable to expand the physics covered by synchrocyclotrons with beam qualities (intensity, duty cycle, emittance) improved by a factor of at least 100.

Beams: The energy has been chosen at approx. 500 MeV where a radial resonance should provide good chances of practically full extraction. This quantitative extraction is a vital condition to the use of high beam currents (over a few 10 μA) as otherwise the machine would get rapidly unserviceable due to induced radioactivity. 500 MeV is well suited to produce very high fluxes of slow mesons and maximum stopped meson densities.

For the production of secondary beams external targets shall be mainly used. The shielding of the target, beam disposal and the purification of the secondary beams raise difficult problems enhanced by the extremely high activation. For the experiments, emphasis will most of the time be on beams of higher purity, emittance, energy resolution and also polarisation rather than high total fluxes. Table I gives fluxes expected after rather conservative calculations.

If highest extraction rates are not attained or simply to allow parallel or parasite experiments, internal targets may also be used in the field free sectors. Due to the strong focussing action of the field and the high gain per turn a large number (approx. 50) of multiple traversals through a 1 MeV thick target could be achieved. This "stacked" beam should yield very high quality secondary beams.

2. Fields of Research

In the physics of elementary particles the most important fields will, as much as it can be foreseen years ahead, be: nucleon-nucleon interaction program with emphasis on polarized beams and especially the neutron interactions. Then precision experiments on pion-nucleon interaction, double pion production, rare pion decays. For muons precise work on intrinsic properties, capture etc. In nuclear structure physics very interesting approaches open: Mesicatoms whose radiation can possibly be analyzed by crystal spectrometers with unprecedented resolution yield charge and magnetic moment distribution inside the nucleus. Muon-nucleus scattering complements corresponding electron experiments. A vast new field are nuclear reactions with pions, like double charge exchange. Finally high resolution inelastic proton events at high energy should give novel information on the dynamical structure of the nuclei. Applications in solid state physics and chemistry will be radiation damage but especially mu-meson chemistry allowing very interesting experiments on binding forces. Of very special interest are biological and medical applications. Beside needed work on biological effects of different particles at all energies, protons can be used for controlled deposition of radiation doses at greater depth for radiation surgery. A very exciting possibility would be the use of negative pions for tumor irradiation. Due to the "stars" formed when they are stopped and absorbed by nuclei, their dose curve with depth is superior by an order of magnitude to radiations like gamma rays or electrons now used. The use of the proton beam to produce neutrons in a subcritical assembly, though not

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delivering very high neutron fluxes at these currents, may be considered, as the possibility of pulsing is attractive in neutron physics applications in relation with nuclear energy problems.

3. Present Status

The type of the accelerator - two stage isochronous ring cyclotron - was chosen in 1963. Preliminary development work including theoretical studies on orbit dynamics as well as model work on magnets and the RF-accelerating system was carried out until the end of 1965 by the ETH cyclotron planning group. The 21 Million Dollar budget based on the project proposal of 1964[3] has now been fully allocated in March 1966 by the Swiss Parliament.

The accelerator shall equip a national research center for nuclear and elementary particle physics and applications to be built at Villigen in the immediate vicinity of the Reactor Research Institute at Würenlingen. Collaboration with the latter in technical and radioactivity matters is considered an important advantage. The center shall provide advanced research facilities to the Swiss Federal Institute of Technology (ETH) and other Swiss Universities. A narrow collaboration with CERN and other research institutions will be sought. The teaching aspect shall remain important though, and some sacrifice on beam intensities seems justified to allow for the flexible and relatively simple operation needed for this.

The time scale foresees 5 to 6 years building time, putting first operation in 1971/72. Close collaboration with industry has been sought in view of the great technical task to be solved. The Oerlikon Engineering Company (MFO) has accepted important technical responsibilities as a general contractor for the construction phase, while ETH is responsible for the basic principles and technical development.

Parallely to the construction of the accelerator facility, research programs shall be prepared in time. It is expected that many contributions will come from Universities of foreign Laboratories presently working with synchrocyclotrons.

In the following chapter we shall try to review the work achieved up to now as well as problems remaining to be solved for the main components and systems of the accelerator. Let us first summarize the main characteristics of the accelerator:

4. Main Characteristics of Accelerator

As a proton accelerator to produce a beam of the required energy, intensity and quality for the Meson Factory Project, the ETH group proposed in 1962, following a suggestion of H.A. Willax, a two stage proton accelerator[1,3], based on the working principle of Sector Focusing Cyclotrons[2]. It consists of a AVF-Cyclotron of conventional design, the "Injector" accelerating protons to a reasonable technical limit (in our case 68-70 MeV) and a high energy stage for further acceleration to 500 MeV. In this second stage, which we call "Isochronous Ring Accelerator", 8 separated C-magnets with specially shaped contours provide the isochronous guide field and beam focussing mainly by the edge effect. Four RF-cavities with a high quality factor, operating on the H_{101}-mode at constant frequency, should allow a high energy gain per revolution at low RF power consumption.

The main advantages we see in this arrangement are:

1. The production of a "CW" beam in a rather economical fashion.

2. Strongly improved conditions for an efficient beam extraction, due to a rather low average guide field (8.3 kGauss at outer radius), a sharp field drop off (narrow pole gap), a high energy gain per turn and defined starting conditions through injection.

3. The possibility for the use of internal meson targets taking advantage of the forward production in a low field region and multiple proton traversals.

4. Access to the beam plane in free sections (for beam collimator, probes, beam controls etc.) and simplification of the mechanical construction and servicing of the activated machine by using standard elements. Flexibility.

Figure 1 shows the general layout and a list of the basic design parameters. (The beam splitter shown between injector and main ring is optional). The pulse frequencies of both machines are matched to the common RF frequency of 50 MHz, the injector revolution frequencies being the third subharmonic of the RF frequency and the main accelerator working on the 6th subharmonic.

Figure 2 shows the structure of the machine. The main parameters of the ring accelerator are:

outer diameter		13-14	meters
beam radius	inner	2	meters
	outer	4.5	meters
height		4.8	meters
total weight		2000	tons
RF power		4 x 60	kW
magnet power		8 x 50	kW

5. Orbit Dynamics and Magnet Model Work

The ring accelerator presents some unusual features influencing strongly the orbit dynamics:
- separated magnets with practically fieldfree (straight) sectors in between
- high flutter values (approx. unity)
- very high field gradients at the edges (see Fig.5)
- small magnet gap (approx. 7 cm)
- sharp field fall-off at outer edge
- unusually large energy gain per turn (1MeV) giving turn separations of 13 mm at injection and 3 mm at extraction radius.

This configuration creates some new problems for the field measurements, data processing and orbit computations. Let us here only summarize the procedures adopted and the results obtained. A detailed account on these calculations is given in a report prepared for this conference by W. Joho and H. Braun[4].

Logically, hard edge calculations were done first. They were complicated by the spiral shape and the varying gap. In fact the magnet structure lies between the case normally encountered in AVF cyclotrons with normal magnet poles and a synchrotron structure. The "Fourier-approach" finally adopted gives - rather astonishingly - better results as the hard-edge-calculations.The first Fourier component dominates and already yields the flutter within 15%, whereas the hard-edge approximation overestimates the flutter by 25%.

The higher Fourier coefficients decrease slowly because of the narrow magnet gap and the high gradients thus produced. Extensive smoothing procedures in azimuthal and radial directions had to be developped until the Fourier components could be used reliably for orbit computing. Coefficients up to order m = 30 per octant give accuracies of approx. 1% on v_r and v_z.

In an attempt to find a field fulfilling the isochronism and focussing conditions required, orbit calculations were based on fields experimentally measured on the 1:5 scale sector magnet models. Instead of actually modifying the magnet pole shape, new fields were mathematically constructed by inserting a flat field part near the hill center, corresponding to a modified pole contour (circular arcs). To isochronize the fields, adjustments in the average field B_o (r) in the order of a few per cent were made.

From an initially quite unsatisfactory focussing (see working point trajectory for first field in Fig. 7) the following steps were taken:

1:5	Sector magnet model with yoke coils Two such sectors to study field superposition
1:5	Sector model with pole coil (Figure 3)
1:5	Same sector with strongly enlarged yoke section, and modified pole gap in function of radius. (Figure 3)

The flow chart for the "mill" used to grind down the measured data is given in Table II. The formula used for the orbit computations are summarized on Figure 4. Calculations for the axial movement do not include at present the higher terms. They are being used in a special study on the linearity of the focussing forces for higher axial betatron amplitudes above 8 mm (small magnet gap of 7 cm!).

A satisfactory mathematical field has been achieved now. It is shown on Figures 5 and 6. Below 500 MeV deviations from isochronism are smaller than 10^{-4} and the small magnet gap gives a field fall-off sharp enough to keep phase slip within 6^o up to 520 MeV. Figure 8 shows the pole contours and the orbits corresponding to this field. According to the working point diagram (Figure 7) v_z stays practically constant and slightly above 0.9 but clearly away from the dangerous $v_z = 1$ resonance. The coupling resonances $v_r + v_z = 2$ and $v_r = 2 v_z$ are also avoided. The few resonances which have to be crossed are listed in Table III. The $v_r = 8/5$ resonance ocurring around 490 MeV has been examined closer and the result is shown in Figure 9. The small initial radial amplitudes and the high gain per turn should allow to cross it without trouble.

A Monte-Carlo investigation was made about tolerances of the magnetic field, considering both real magnet errors and such introduced by positioning errors in the measurement due to the high field gradients. Figure 10 shows how these random errors are reduced from initially 150 Gauss to 1 Gauss by Fourier and radial smoothing. Therefore tolerances of ± 2 Gauss and ± 0.5 mm should be acceptable and relatively easy to meet.

In conclusion these investigations show that small changes mainly in the radial gradient of the average magnetic field drastically affect the working point trajectory in the $v_z - v_r$ diagram, but that on the other hand rather easy shimming methods allow to obtain almost any desired path without abandoning the circular edges of the magnet.

6. Magnet Design

Because of their shape and size, the small gap and the high accuracy required, the C-shaped sector magnets raise difficult design problems. First the yoke structure was studied on a non-spiralled 1:10 scale model and then two 1:5 spiral sector models constructed. Computations by relaxation techniques were carried out to study saturation, but showed of little effectiveness for the complicated three-dimensional spiral structure.

As space is very scarce between the magnets by the presence of the RF cavities, a first design was tried with poles around the yoke neck. It rapidly became clear however that the strong stray field significantly changed orbit dynamics and that especially the tricky problem of the influence on one magnet by its neighbors (non-additive superposition of fields) was considerably enhanced.

Therefore one of the magnets was equiped with pole coils and at the same time additional yoke iron added, as the saturation had been underestimated in the first 1:10 model. (Figure 3). As discussed in the previous section, the gap was recut (2% change) to approximate more closely the desired field, though the wrong width of the model was corrected only mathematically.

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Based on these results, two new magnets have been designed and will be constructed by MFO:

1. a new 1:5 model with sector shape, gap and yoke section as close as possible to the wanted field. (To be ready by middle 1966).

2. a full scale sector magnet model whose yoke is frozen, but whose pole plates shall be determined after the measurements on the new 1:5 model. (To be completed in spring 1967).

The yoke and coils have been designed with space considerations in mind and to meet the usual minimum of initial and operating costs. Details on the design work on these magnets are given in a report prepared by R. Wolgast and A. Létay for this conference.[5]

The 1:1 model magnet is drawn in Figure 11. Its weight is 230 tons. In order to maintain high stability it is necessary to take up the strong forces (magnetic: 260 tons, vacuum and weight: 70 tons) by supports at the inner and outer radius.

It is expected from the studies made, that the initial field errors will be of the order of ± 100 Gauss due to accumulated machining errors and ± 60 Gauss due to inhomogenities in the magnetic properties of the iron. It is planned to reduce these to ± 10 Gauss by individual shimming. Shimming can be added on the pole faces or also at the edges, allowing some individual correction of both mean field and flutter. The final adjustment inside these ± 10 Gauss will be done by a limited number of trim-coils (7 pairs per sector). The low power needed will simplify the design.

Preparatory work has been done on the power supplies of the magnets and the problem of adjusting them individually, and also on a special, remote and radiation-resistant nuclear magnetic resonance probe to be used as field stabilizing element.

7. High Frequency Accelerating System

The main advantage of the ring accelerator with injection is to provide space for a low loss RF system able to supply very high voltage gains per turn. Rectangular cavities (slightly tapered in radial direction in the final version) oscillating in the H_{101} mode at 50 MHz (sixth harmonic of revolution frequency) are used. The cavities shall be excited by individual amplifiers driven by a same master oscillator (also controlling the injector cyclotron) through networks allowing precise phase and amplitude adjustment and servo-control. Gap voltages of 350 kV peak are desirable. With a Q-value around 30'000 only moderate RF power (50 kW) is needed.

Development started by theoretical investigations and then 1:5 scale models in copper were built. Q-value, voltage distribution along the gap, coupling loops and tuning methods were investigated. Satisfactory methods for precise phase measurements were developped.

After this, a full scale cavity in a vacuum vessel was built to study the voltage holding in the gap. No commercial amplifier could be found and a first powerstage with a Tetrode EIMAC 4 CW 50'000 in grounded cathode mode was built. (Figure 12). It is driven by a 1 kW master-oscillator and buffer assembly.

The cavity itself was constructed as a plug-in unit made from aluminium sheet with blown up cooling tubes, and plated on the inside by 0.1 mm silver sheet. The whole cavity is fastened on the inside of the lid of the large vacuum tank and the powerstage is fixed on the other side of the lid. The inside dimensions of the vacuum vessel are 5.7 x 3.2 x 0.8 meters. The model is also intended for studies on the vacuum system, therefore various pumps, as oil diffusion pumps with or without liquid air baffles, and ion-getter pumps, can be fitted to a side chamber. (Figure 13).

A more detailed account of the design and the first results obtained with the 1:1 RF cavity working model is given in a special report prepared for this conference by P. Lanz, H. Frei and J. Bänteli.[6]

The main steps were the following: At atmospheric pressure voltages up to 150 kW were reached before discharges occured. The latter took the form of sparks then rising as arcs, and these sometimes rose further as a kind of separated ball lightning vanishing later with a little explosion.

In vacuum (2×10^{-6} Torr without discharge) for a very long time discharges occured at low voltages (below 10 kV) and one did not succeed passing through to higher voltages. This effect was attributed to a discharge (possibly multipactoring) which had two effects: changing the load on the amplifier so that the match was bad, secondly outgassing produced other types of discharges. Difficulties were also encountered with the powerstage: the cavity being used directely as the plate load, too little freedom for matching remained. An improved powerstage with tunable plate tank circuit is in construction now. (Figure 12).

The passage through the discharge region was finally achieved by the following means:

Feedback to produce self-oscillation to give more power for baking out.

Liquid-air traps to improve vacuum.

fast turning on of RF by a mercury relay.

(At present none of these measures seem to be really required any more to get through the discharge region). After these measures voltage could be step-wise increased to 100-150 kV. After resolving some trouble by cooling the coupling loop and building a new blocking condensor between the plate of the power tube and the coupling loop, stable operation at 200 kV was obtained. Peaks up to 320 kV are reached at present, though only in unstable operation due to two causes:

Periodic gas release by surface heating
Mechanical oscillations of the cavity excited by electrostatic forces (approx. 10 Hz).

Continous analysis of the rest gas with a mass spectrometer leak detector shows clearly that most of the released gases are cracking products of pump oil deposits on the surfaces. These discharges create electrons and enhance dangerously the X-ray intensity which becomes uncomfortably high at 300 kV. Future work will be concentrated on power stage design and study of the vacuum requirements. Possibly an integrated cavity, being its own vacuum vessel, will be considered. Phase and voltage control systems will be developped for the 1:1 cavity. If possible, studies on the factors setting an ultimate limit on voltage holding will be undertaken.

It can be concluded that the goal of 1 MeV energy gain per turn should be attainable without particular difficulties.

8. Injection and Extraction

Injection: The injector cyclotron has to deliver a beam of 70 MeV protons with a 50 MHz pulse frequency and with a very good beam quality in order to allow injection into the ring accelerator without loss and ensuring small initial betatron amplitudes. Energy spread of 0.2% and 30 mm mrad in both directions are desirable, and though difficult, should be possible.

It is planned to buy the injector from an industrial firm and several offers have been submitted.

The injection mechanism into the ring accelerator, though simple in principle with the radial turn separation of 15 mm, is difficult due to extreme lack of space and the requirement that one not disturb the magnetic field of the main magnets in the range of normal orbits. The system being designed now uses first an injection magnet with low stray field (possibly a current sheet septum magnet) and then an electrostatic injection channel in the second to next sector to make the beam tangential to the injection orbit (Figure 14). Detailed studies are under way with a general orbit code modified to allow the tracing of beams through special field regions. In order to bring the beam from the injector to the first injection magnet, different possibilities are considered: crossing through beam the plane at the opposite free sector or the same slightly above midplane, or finally vertically from above through 90° bending magnets. The decision shall be made on engineering aspects mainly, as beam optics can be solved in any case.

Extraction: No extraction system has been worked out in detail yet, as precise knowledge of the field structure at outer radius from the full scale magnet sector will be needed. Two possibilities seem promising:

- Resonance extraction at $v_r = 3/2$. According to the hard edge calculations done in 1963 this resonance occured around 500 MeV. With the new fields based on 1:5 Model work, probably due to the added requirement of circular pole contours, the first crossing of the resonance occurs at 420 MeV (which is too low for meson production) and then a second rapid crossing takes place at 516 MeV when the field rise with radius starts to decrease at the magnet edge. (See Figure 7). It is expected that the first crossing of this resonance (non essential with 8 sectors) should be easy. Preliminary calculations show that a strong local third harmonic bump (two magnets of opposite polarity in field free sectors and separated 90° in phase of radial oscillation) would suffice in building up a large coherent amplitude in a few turns.
- Electrostatic extraction by means of "transparent" septum and a magnetic channel in the second next free sector (Figure 15). This is a straightforward possibility which may, from first estimation, allow a 90% extraction rate at current levels above 50 μA.

It is apparent that these extraction schemes, or even a combination of both, benefit largely from the initial attempt to lay out the accelerator in view of quantitative extraction: low magnetic field, small magnet gap, field free sectors, high energy gain per turn and phase space control by injection.

9. Engineering

Several engineering studies have been carried out in view of the building lay out. These include the cooling requirements of the accelerator and experimental beam guiding systems and the investigation of the possibilities of using cooling towers, river water or ground water as final heat sink, the last alternative looking at present most attractive.

Similar studies on the supply of electrical energy have been made and some succesful development work on SCR-rectifiers done. In both cooling and supply studies MFO has taken an active part.

The mechanical lay-out of the shielding and especially the difficult problem of the external production target for secondary beams have received only preliminary attention due to lack of capacity.

The major engineering problem faced is the design of the vacuum chamber. Especially the interface with the sector magnets poses very tricky problems. Among the different possibilities looked at was first an independent vacuum chamber inside the magnet gap. But even with several supports through the magnet pole faces, or with a double vacuum system, the pole gap, further reduced by the trimcoils, proved too small. The magnet had therefore to be used as part of the vacuum system. Figure 16 shows a design sketch in the direction pursued at present.

Due to the high radiation fluxes (mostly fast neutrons) expected, the question of vacuum seals is a vital one, as in certain places organic seals like highly radiation resistant polyurethane elastomers will have lifetimes as short as 6 months. Metal seals, on the other hand, with the strong pressing forces required, are very cumbersome in the narrow and inaccessive space between magnet and cavity. Permanent sealing by welding thin stainless steel sheets has been considered and looks very attractive and rather simple for the final operating state. For the starting phase of such a new and rather complex accelerator it seems too risky though. A system using standard organic seals but being very easily interchangeable is now considered best. Figure 16 shows this pneumatic sealing flange which can be squeezed for removing by pumping it out. A first model made from aluminium is ready, but not yet tested sufficiently.

A further engineering task of great importance, but which is also only beginning, concerns the whole complex mechanical structure of the machine in view of assembly and servicing once highly radioactive.

The control and safety interlock system will be very demanding, as several elements like injector, main accelerator, external target and some experiments will have to be included in situations difficult to foresee and likely to vary considerably. A centralized computer control is therefore considered, and preliminary studies have been started.

Another important development is the construction of a magnetic field measuring machine for the full scale magnet sectors. The large size and high field gradients create difficult mechanical problems. The system of a "rabbit" moving radially with cycloidal drive as developped in UCRL has been adopted. Sensing elements will be either Hall probes of preferably miniature coils to be used with high stability integrator. Automatic programming and punched tape output is included.

10. Buildings and Site

Figure 17 shows a lay out sketch of beams expected to be used, and Table I lists the tentative characteristics of these beams. The intrinsic insecurity on the extraction rate to be obtained calls for maximum flexibility of the arrangement and therefore the following principles have been set:

- A large main hall (50 x 90 meters) shall house both accelerator and the experiments
- Machine shielding shall be completely demountable and closely packed around the accelerator
- The main hall is to be slightly sunk into ground, but unshielded, therefore:
- Beams leaving the main shielding or the external target shall be only purified secondary beams and never primary full intensity beams.
- Experiments shall be shielded, so that the presence of experimenters of setting up operations may be permitted at least in a part of the cases.

Figure 18 shows a cross section of the hall and arrangement of the accelerators and their shielding. A 50 ton crane is provided. Cooling and power shall partly be distributed from conduits along the walls of the hall.

Figure 19 shows the site and the disposition of the buildings. The operations building alongside the main hall shall house the cooling systems and electrical supplies and the control room for the accelerators. Counting rooms and laboratories and offices for the initial phase will be included and further laboratory buildings erected as needs grow. Extension of high activity zone is free to the south and the east along the river, whose rather high banks provide useful safety distance.

The construction of the electrical power station, heating plant, water plant and of the bridge connecting to the Reactor Institute shall be started in 1966, the hall and operations building in 1967.

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TABLE I BEAM CHARACTERISTICS OF ETH MeV RING-ACCELERATOR

1) External Proton Beam of Injector (68 ± 0,25) MeV, pulse length 1...5 nsec, pulse separation 20 nsec

2) External Proton Beam (510^{+1}_{-2}) MeV, Maximum RF duty cycle = 25%
Minimum pulse length 0,5 nsec, pulse separation 20 nsec

3) Secondary beams

Beam	Energy (MeV)	Intensity (sec^{-1})	Area	Remarks	Intensity of protons (μA)	Target
π^+	150 ± 3	$1{,}5 \cdot 10^7$	$0{,}8\ cm^2$	-	10 intern	C_{12} $0{,}4\ g/cm^2$
π^-	"	10^6	"	-	"	"
π^+	"	$2{,}2 \cdot 10^8$	"	-	75 extern	C_{12} $9\ g/cm^2$
π^-	"	$1{,}6 \cdot 10^7$	"	-	"	"
$\mu^{\pm}$	150 ± 12	$2 \cdot 10^7$	$100\ cm^2$	2% π^+	"	"
μ	"	$7 \cdot 10^5$	"	2% π^-	"	"
Pol. p	490 ± 2,5	$2 \cdot 10^{10}$	$1\ cm^2$	50% polarization scatt. angle 7°	"	C_{12} $5\ g/cm^2$
Pol. n	490 ±	$8 \cdot 10^6$	$20\ cm^2$	30% Polarization scatt. angle 7° 10 m distance	"	D_2 $4\ g/cm^2$
γ from π^0	Max. at 150	10^7	$10\ cm^2$	10 m distance	"	C_{12} $9\ g/cm^2$
v from $\pi^{+\,\mu}\mu^+ + v_\mu$	30	$2 \cdot 10^8$ pro	cm^2	"	"	-

TABLE II ORBIT-CALCULATIONS FROM MAGNETIC FIELD MEASUREMENTS

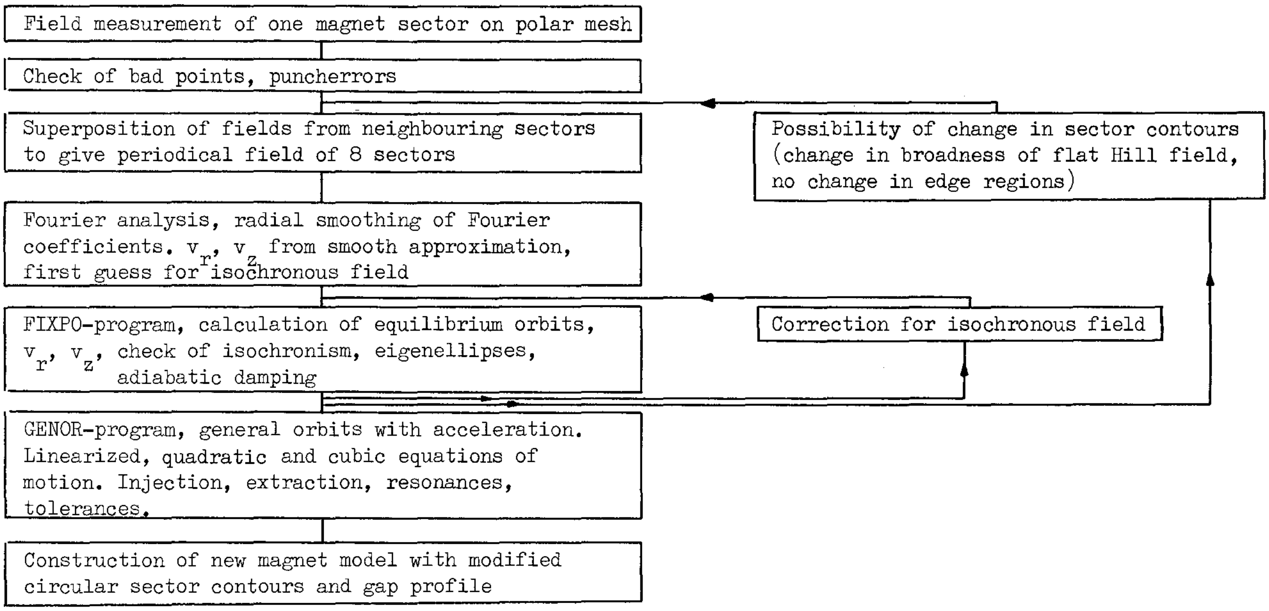

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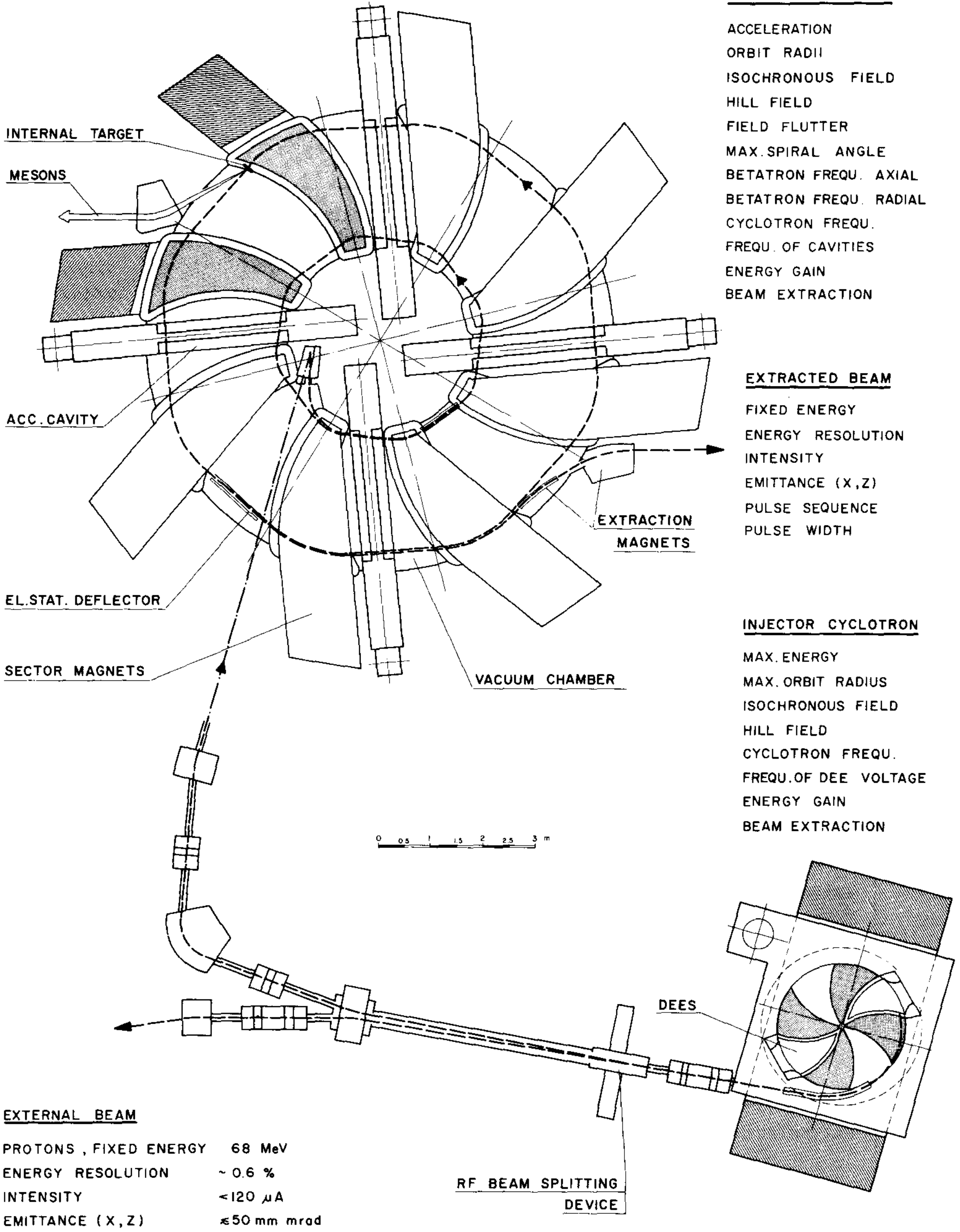
TABLE III RESONANCES OF INTEREST FOR THE ETH RINGCYCLOTRON

general form: $n\, v_r + m\, v_z = p$

Resonance	Order	Energy	Type of error necessary	Mainly driven by	Effect
$v_z = 1$	linear	injection	twisted median plane	1.harmonic of B_r, B_θ in median plane	axial displacement of equilibrium orbit
$v_r + v_z = 2$	linear	injection	twisted median plane	2.harmonic of $\frac{\delta B_r}{\delta r}$, $\frac{\delta B_\theta}{\delta r}$, $\frac{\delta B_z}{\delta z}$ in median plane	couples radial into axial oscillation. Growth of axial amplitude.
$v_r = 3/2$	linear	420 MeV extraction (515 MeV)	non identical magnets	3. harmonic of B, $\frac{\delta B}{\delta r}$	exponential growth of radial amplitude. Resonant beam extraction with bump ?
$v_r - 2v_z = 0$	quadratic	extraction	none	$\frac{\delta^2 (B)}{\delta r^2}$	couples radial into axial oscillations. Growth of axial amplitude.
$v_r = 4/3$	quadratic	300 MeV	misalignement	4.harmonic of $\frac{\delta B}{\delta r}$, $\frac{\delta^2 B}{\delta r^2}$	no effect for "normal" radial amplitudes
$v_r + 3v_z = 4$	cubic	injection extraction	twisted median plane	4.harmonic of B_r, $\frac{\delta B_r}{\delta r}$ in median plane	same as $v_r + v_z = 2$ but much less important
$3\, v_z - v_r = 1$	cubic	extraction	twisted median plane	1.harmonic of B_r, $\frac{\delta B_r}{\delta r}$ in median plane	" "
$v_r = 5/3$	quadratic	extraction ?	misalignement	5.harmonic of $\frac{\delta B}{\delta r}$, $\frac{\delta^2 B}{\delta r^2}$	growth of radial amplitude. Resonant beam extraction with bump ?
$v_r = 8/5$	4th	extraction	none	mainfield	no effect for "normal" radial amplitudes.

ISOCHRONOUS ACCELERATOR FOR 500 MeV PROTONS



RING ACCELERATOR

ACCELERATION	68 – 510 MeV p
ORBIT RADII	2.0 – 4.4 m
ISOCHRONOUS FIELD	0.58 – 0.83 Vs/m²
HILL FIELD	1.4 – 1.8 Vs/m²
FIELD FLUTTER	~ 1.0
MAX. SPIRAL ANGLE	~ 34°
BETATRON FREQU. AXIAL	0.9 – 0.8
BETATRON FREQU. RADIAL	1.05 – 1.55
CYCLOTRON FREQU.	8.3 Mc/s
FREQU. OF CAVITIES	49.8 Mc/s (6. harm.)
ENERGY GAIN	~ 1 MeV / rev.
BEAM EXTRACTION	at ν_r = 1.5

EXTRACTED BEAM

FIXED ENERGY	~ 510 MeV
ENERGY RESOLUTION	~ 0.4 %
INTENSITY	~ 30 – 80 μA
EMITTANCE (X, Z)	≲ 30 mm mrad
PULSE SEQUENCE	20 (40) ns
PULSE WIDTH	~ 1 – 5 ns

INJECTOR CYCLOTRON

MAX. ENERGY	68 – 70 MeV p (H^-)
MAX. ORBIT RADIUS	1.1 m
ISOCHRONOUS FIELD	108 - 1.16 Vs/m²
HILL FIELD	1.7 Vs/m²
CYCLOTRON FREQU.	16.6 Mc/s
FREQU. OF DEE VOLTAGE	49.8 Mc/s (3. harm.)
ENERGY GAIN	~ 0.2 MeV / rev.
BEAM EXTRACTION	at ν_r = 1.0

EXTERNAL BEAM

PROTONS, FIXED ENERGY	68 MeV
ENERGY RESOLUTION	~ 0.6 %
INTENSITY	< 120 μA
EMITTANCE (X, Z)	≲ 50 mm mrad
PULSE SEQUENCE	20 ns
PULSE WIDTH	~ 1 - 6 ns

Figure 1.

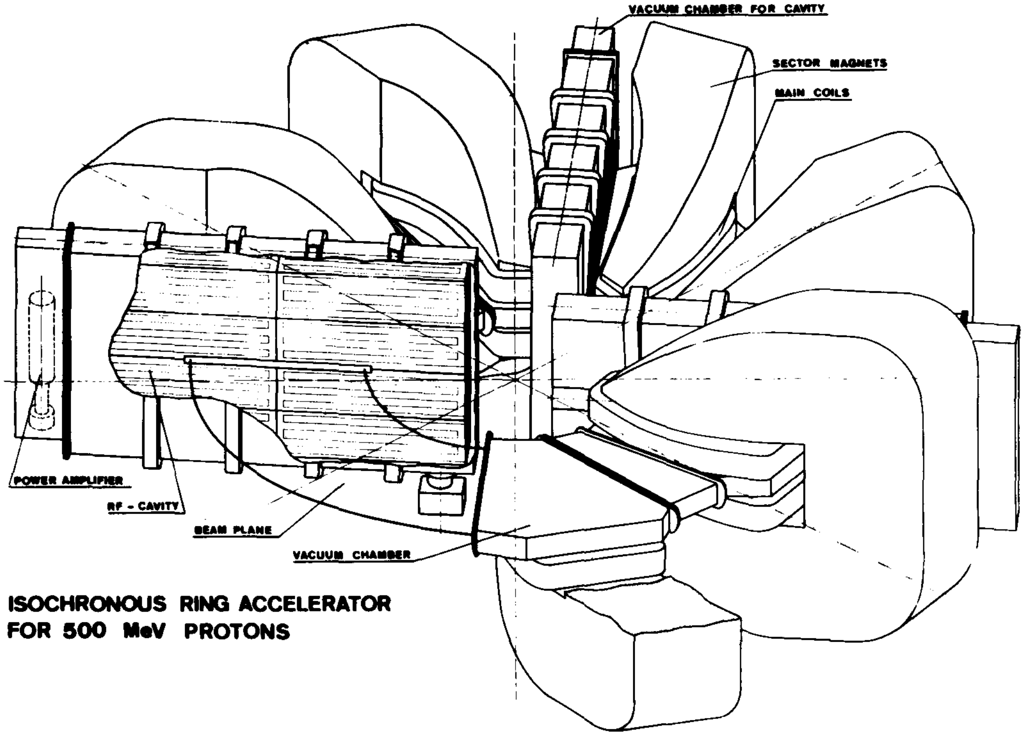


Figure 2.

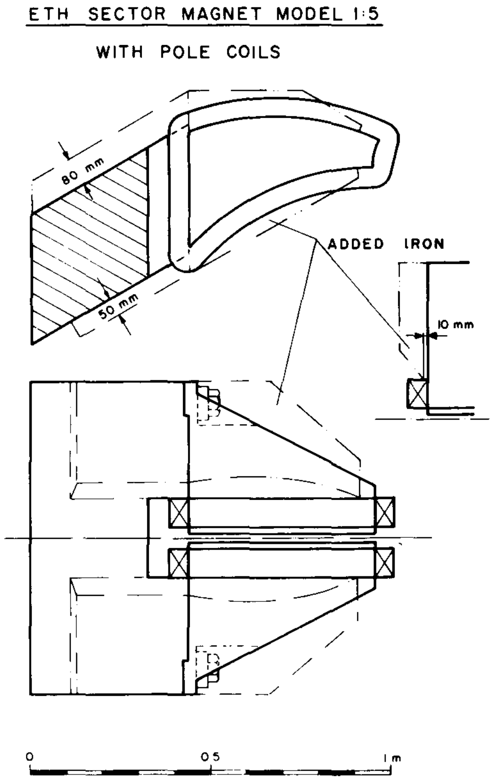


Figure 3.

EQUATIONS OF MOTION FOR PROTONS IN A MAGNETIC FIELD $\underline{B}(r,\theta,z)$

FIELD IN SYMMETRY PLANE : $B(r,\theta) = -B(r,\theta,z=0)$

PERIOD : $\theta_0 = \frac{2\pi}{N}$

$$-B_r = z \cdot \frac{\partial B}{\partial r} - z^3 f_3 + \cdots$$

$$-rB_\theta = z \cdot \frac{\partial B}{\partial \theta} - z^3 g_3 + \cdots$$

$$-B_z = B - z^2 \cdot f_2 + z^4 f_4 \cdots$$

$$f_2(r,\theta) = \frac{1}{2}\left(\frac{\partial^2 B}{\partial r^2} + \frac{1}{r}\frac{\partial B}{\partial r} + \frac{1}{r^2}\frac{\partial^2 B}{\partial \theta^2}\right)$$

$$f_3(r,\theta) = \frac{1}{6}\left(\frac{\partial^3 B}{\partial r^3} + \frac{1}{r}\frac{\partial^2 B}{\partial r^2} - \frac{1}{r^2}\frac{\partial B}{\partial r} + \frac{1}{r^2}\frac{\partial^3 B}{\partial r\,\partial \theta^2} - \frac{2}{r^3}\frac{\partial^2 B}{\partial \theta^2}\right)$$

$$g_3(r,\theta) = \frac{1}{6}\left(\frac{\partial^3 B}{\partial r^2\,\partial \theta} + \frac{1}{r}\frac{\partial^2 B}{\partial r\,\partial \theta} + \frac{1}{r^2}\frac{\partial^3 B}{\partial \theta^3}\right)$$

$$f_4(r,\theta) = \frac{1}{24}\left(\frac{\partial^4 B}{\partial r^4} + \frac{1}{r^4}\frac{\partial^4 B}{\partial \theta^4} + \frac{2}{r^2}\frac{\partial^4 B}{\partial r^2\,\partial \theta^2} + \frac{2}{r}\frac{\partial^3 B}{\partial r^3} - \frac{2}{r^3}\frac{\partial^3 B}{\partial r\,\partial \theta^2} - \frac{1}{r^2}\frac{\partial^2 B}{\partial r^2} + \frac{4}{r^4}\frac{\partial^2 B}{\partial \theta^2} + \frac{1}{r^3}\frac{\partial B}{\partial r}\right)$$

θ = INDEPENDENT VARIABLE

$$1)\quad p_r' = p_\theta - rB + \underbrace{rz^2 \cdot f_2 + \frac{z\,p_z}{p_\theta}\frac{\partial B}{\partial \theta}}_{\text{QUADRATIC}} - \underbrace{rz^4 \cdot f_4 - \frac{z^3 p_z}{p_\theta} g_3}_{\text{4th ORDER}}$$

$$2)\quad r' = r \cdot \frac{p_r}{p_\theta}$$

$$3)\quad p_z' = -z \cdot \frac{p_r}{p_\theta}\frac{\partial B}{\partial \theta} + rz \cdot \frac{\partial B}{\partial r} + \underbrace{z^3 \frac{p_r}{p_\theta} g_3 - rz^3 f_3}_{\text{3rd ORDER}}$$

$$4)\quad z' = r \frac{p_z}{p_\theta}$$

$$5)\quad t' = \frac{r}{p_\theta} \cdot \gamma$$

$$p_\theta \equiv \sqrt{p^2 - p_r^2 - p_z^2}$$

Figure 4.

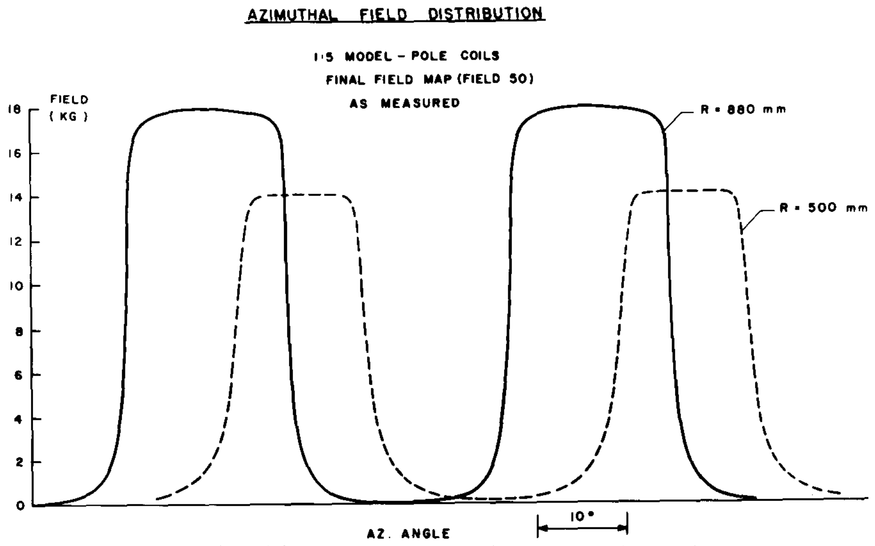
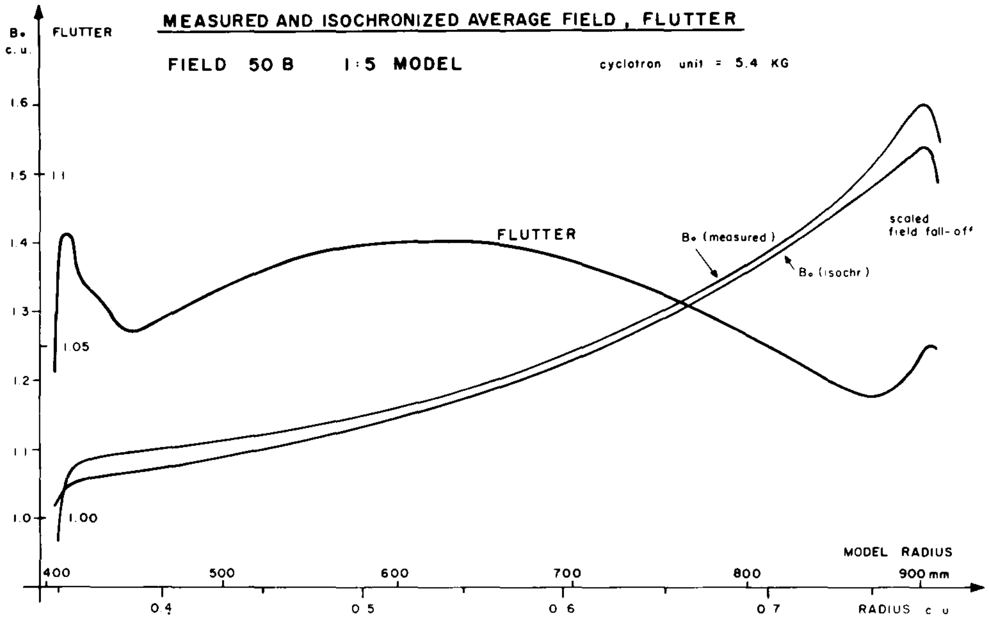


Figure 5.



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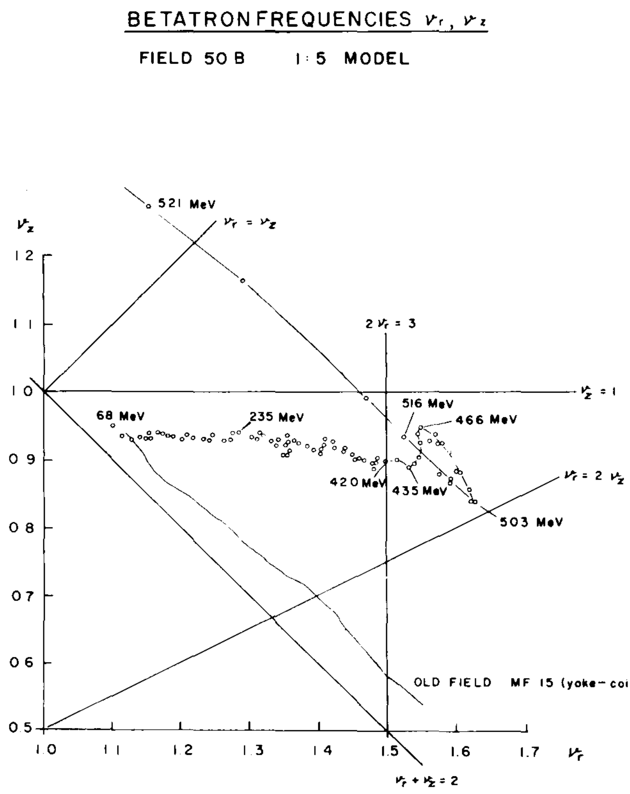

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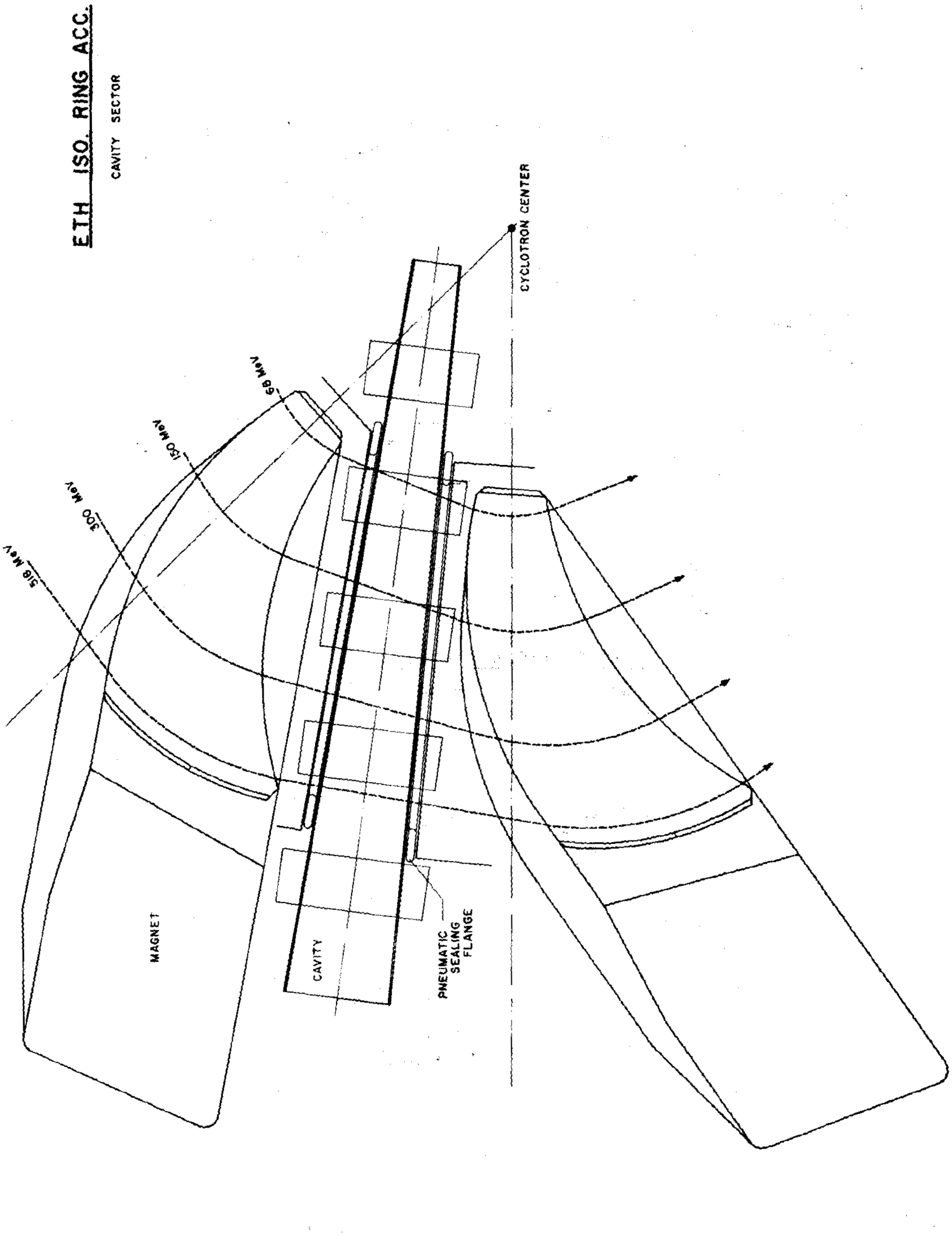

Figure 8.

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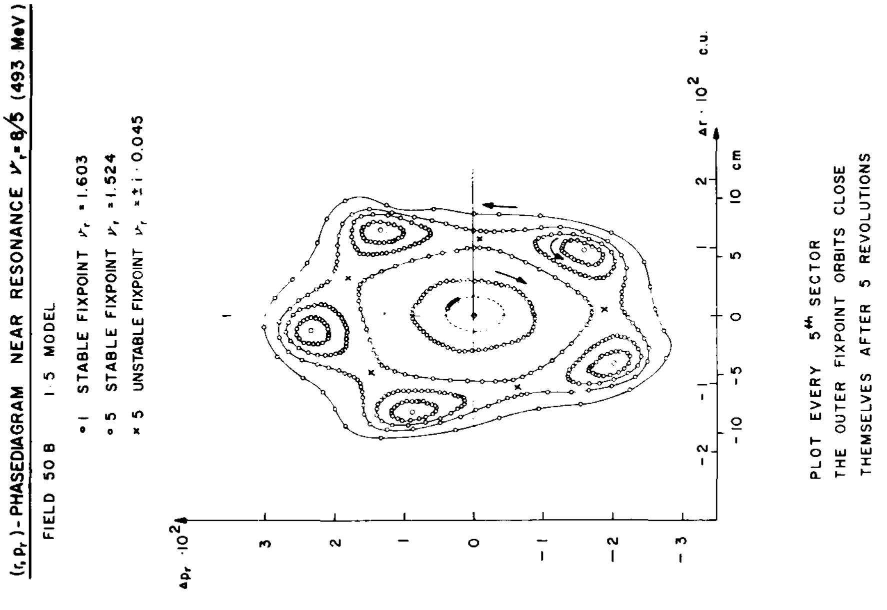

PLOT EVERY 5th SECTOR
THE OUTER FIXPOINT ORBITS CLOSE
THEMSELVES AFTER 5 REVOLUTIONS

Figure 9.

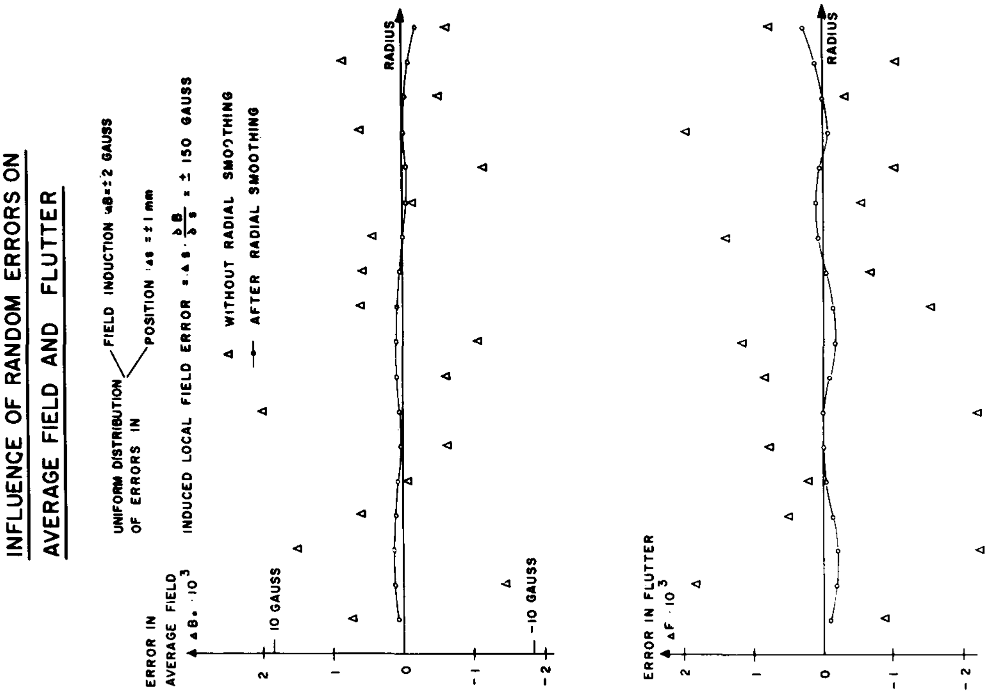

Figure 10.

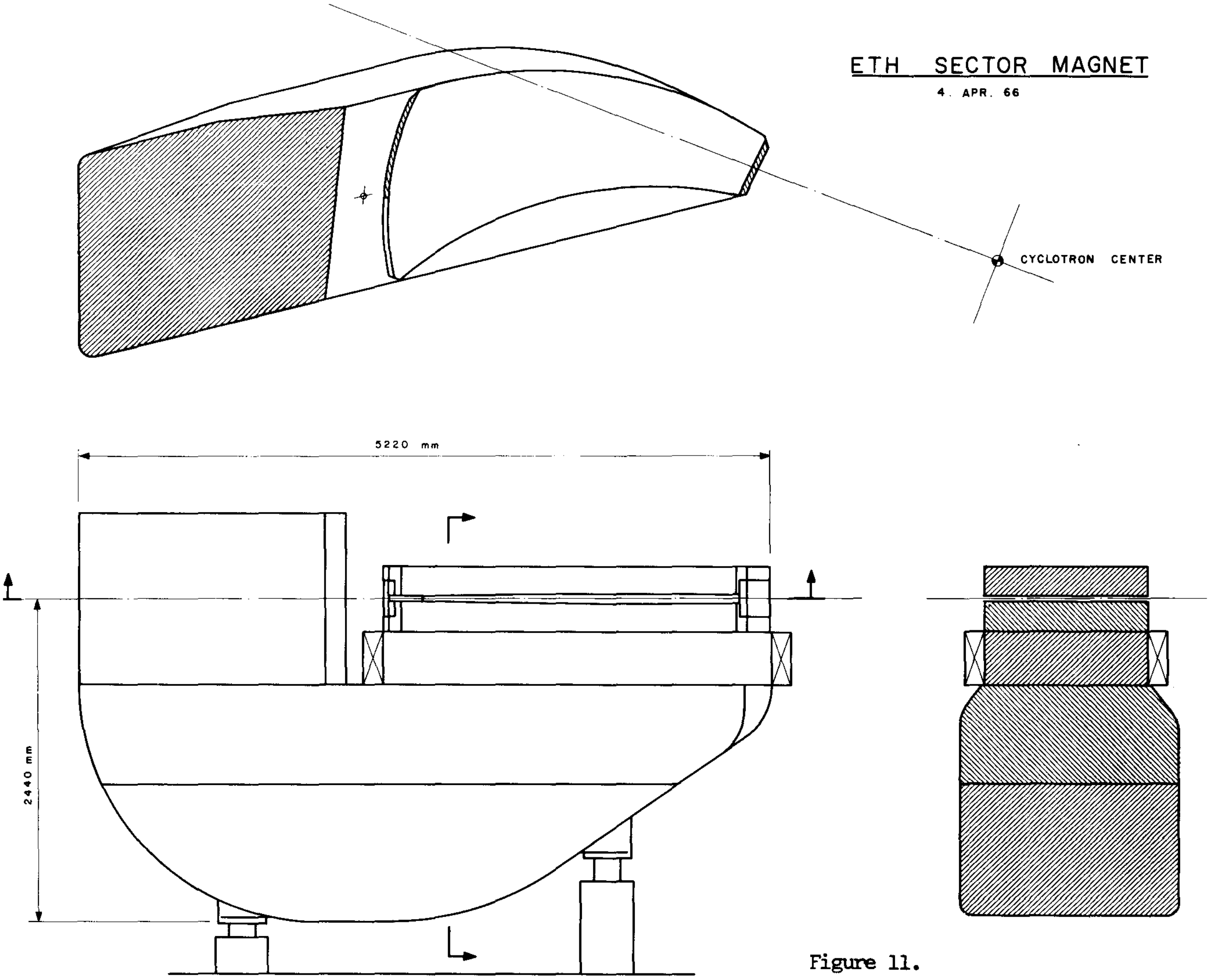

Figure 11.

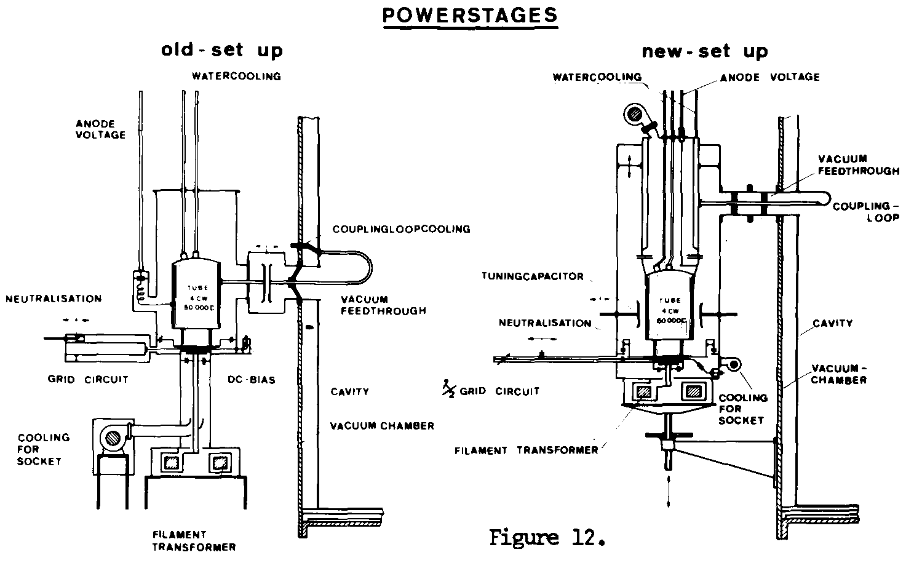

Figure 12.

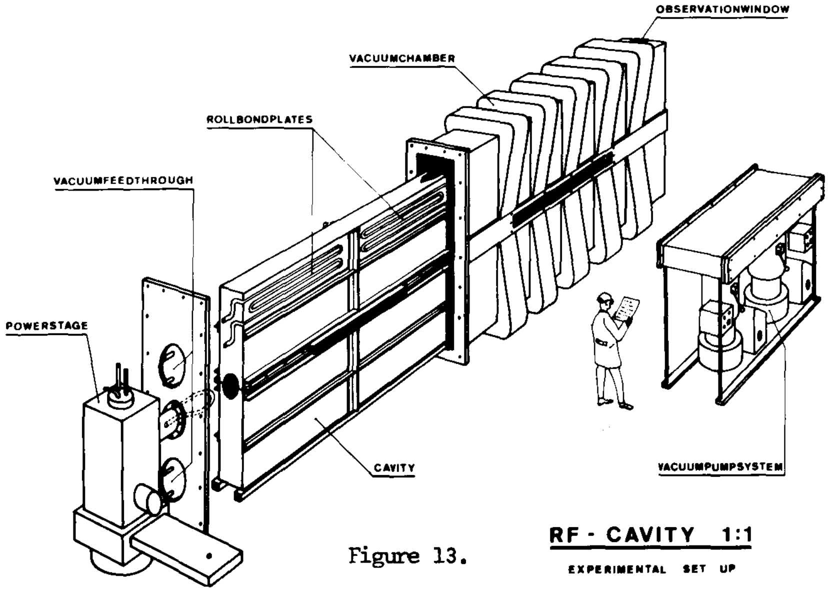

Figure 13.

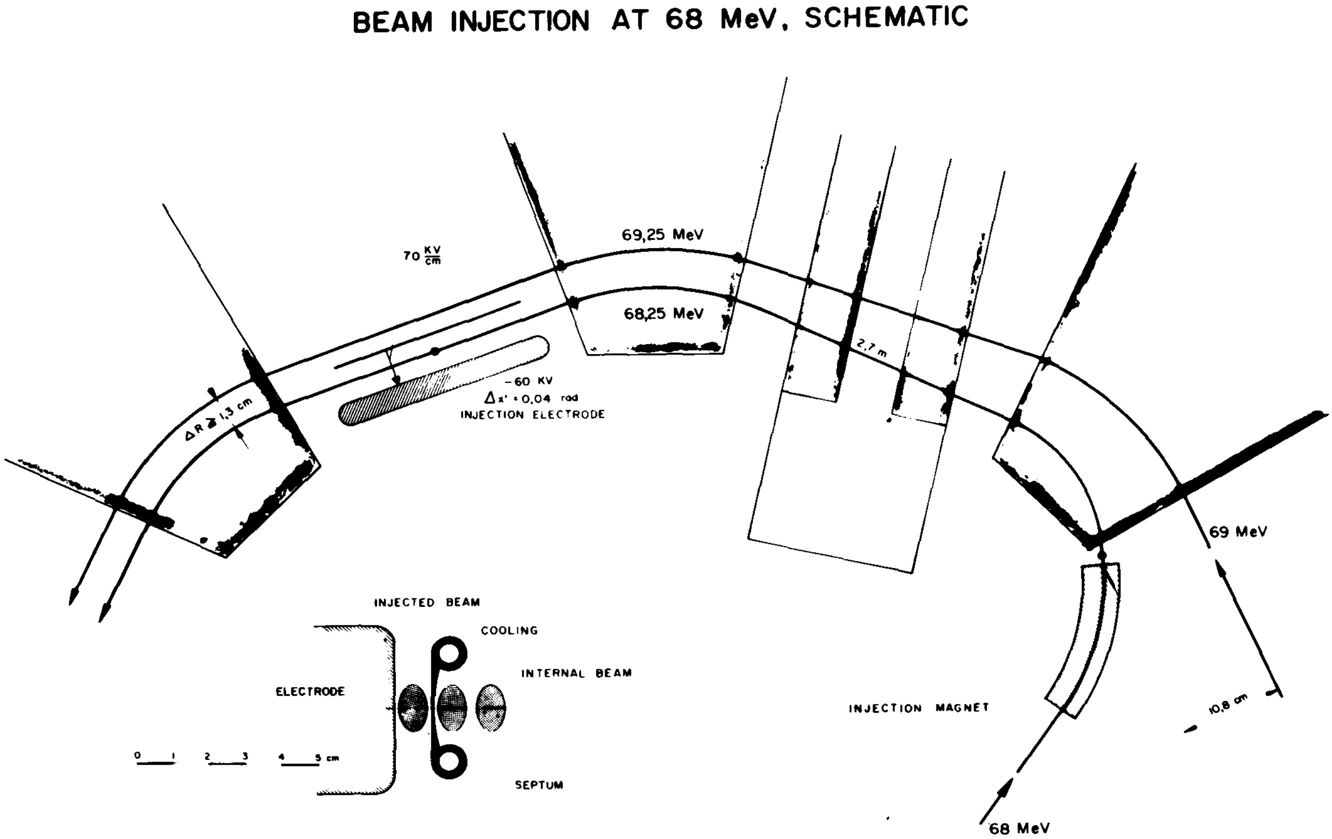

Figure 14.

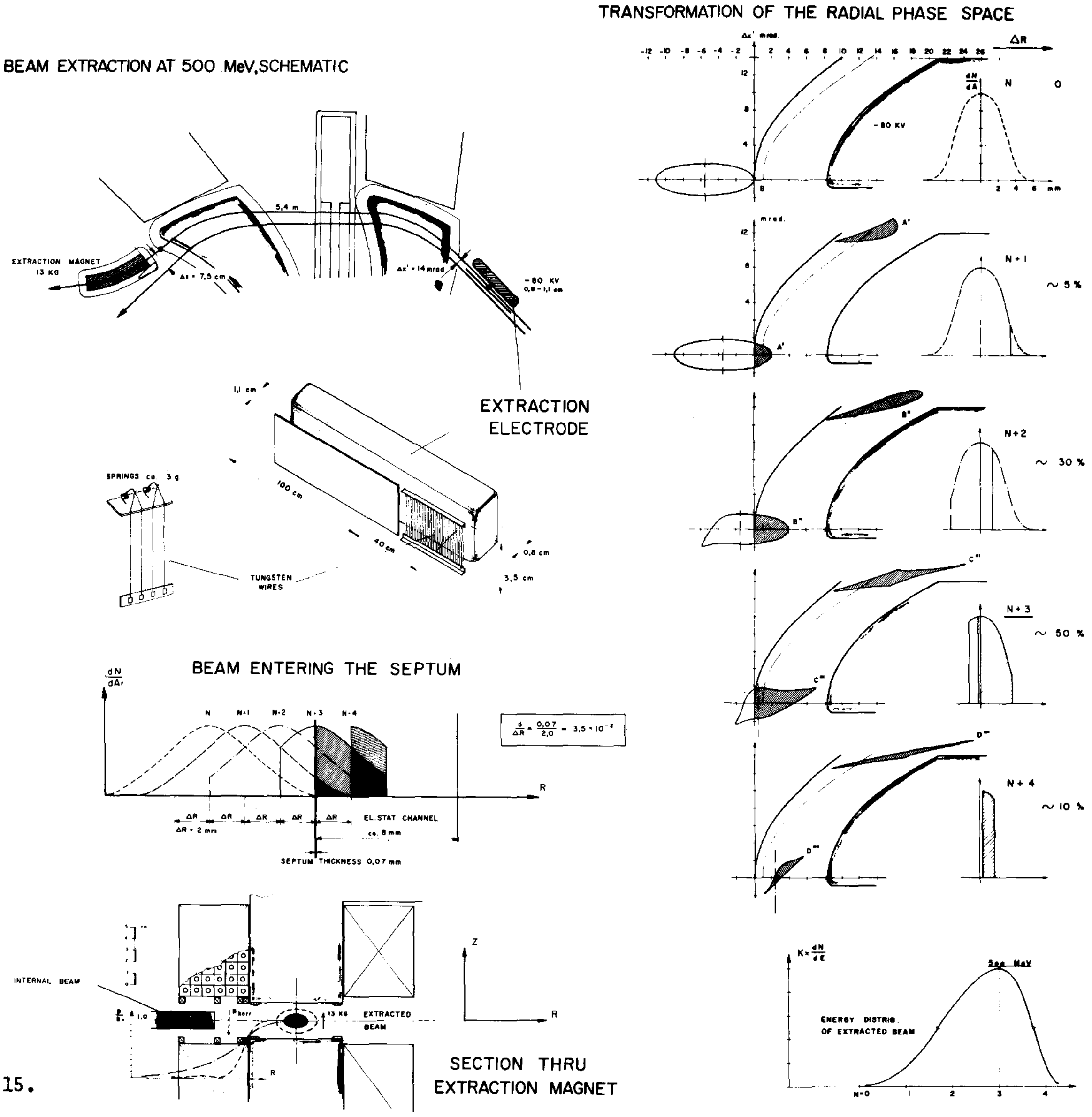

Figure 15.

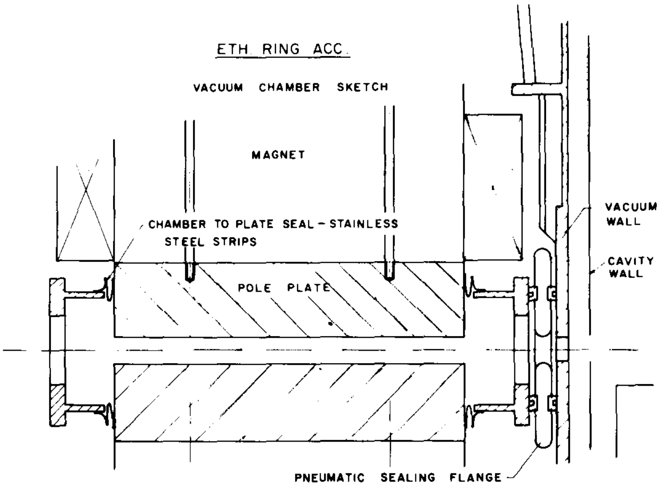

Figure 16.

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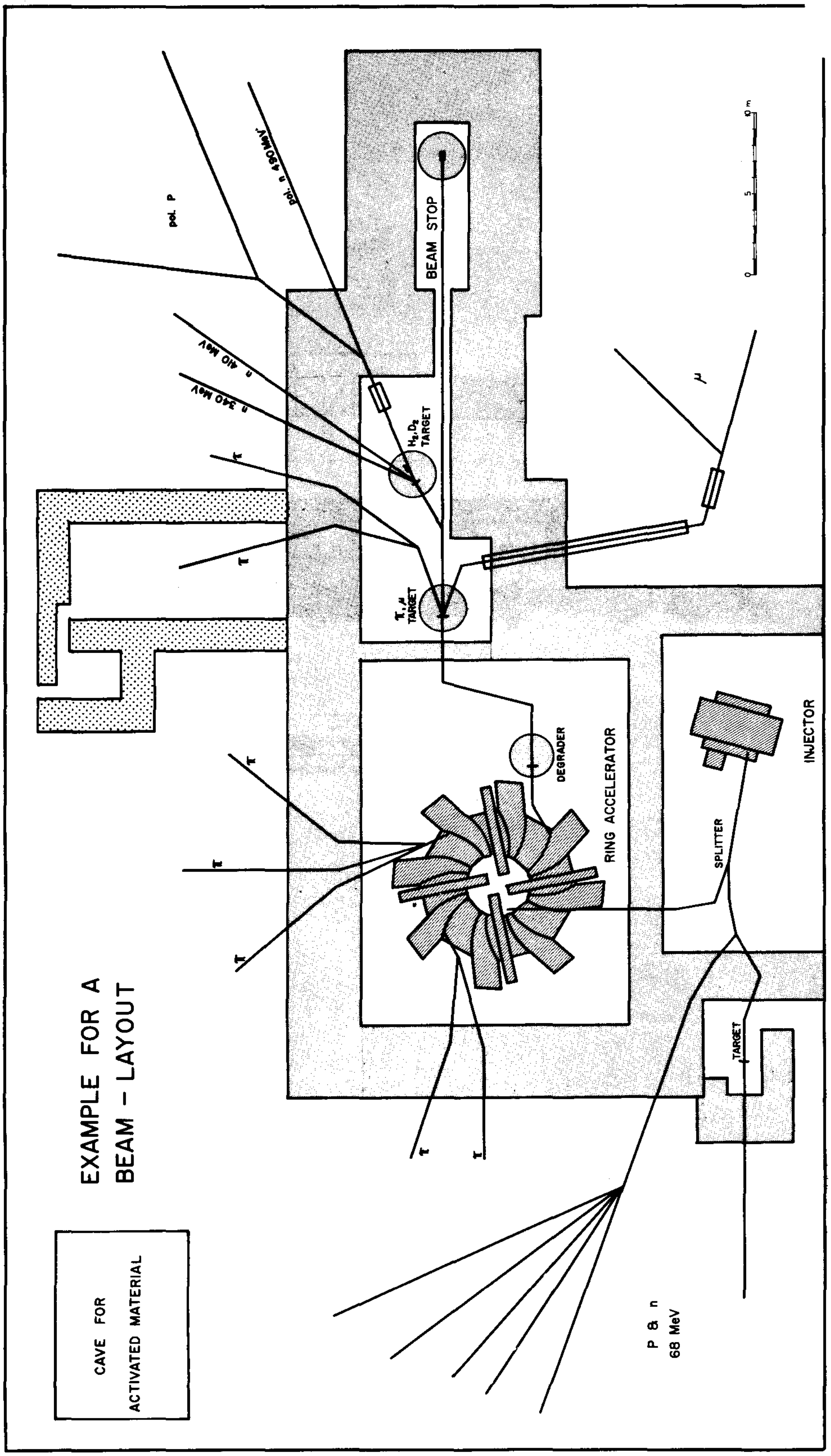

EXAMPLE FOR A
BEAM - LAYOUT
CAVE FOR
ACTIVATED MATERIAL
pol. P
pol. n 480 MeV
n 410 MeV
n 340 MeV
π
π
BEAM STOP
H_2,D_2 TARGET
π, μ TARGET
μ
0
5
10 m
DEGRADER
RING ACCELERATOR
INJECTOR
SPLITTER
π
π
π
π
π
TARGET
P & n
68 MeV

Figure 17.

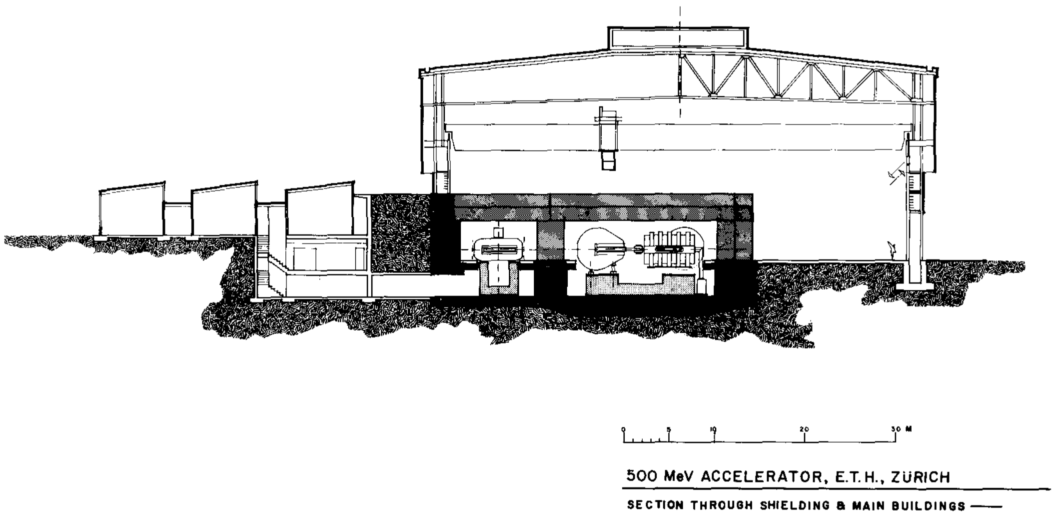

0
5
10
20
30 M
500 MeV ACCELERATOR, E.T.H., ZÜRICH
SECTION THROUGH SHIELDING & MAIN BUILDINGS

Figure 18.

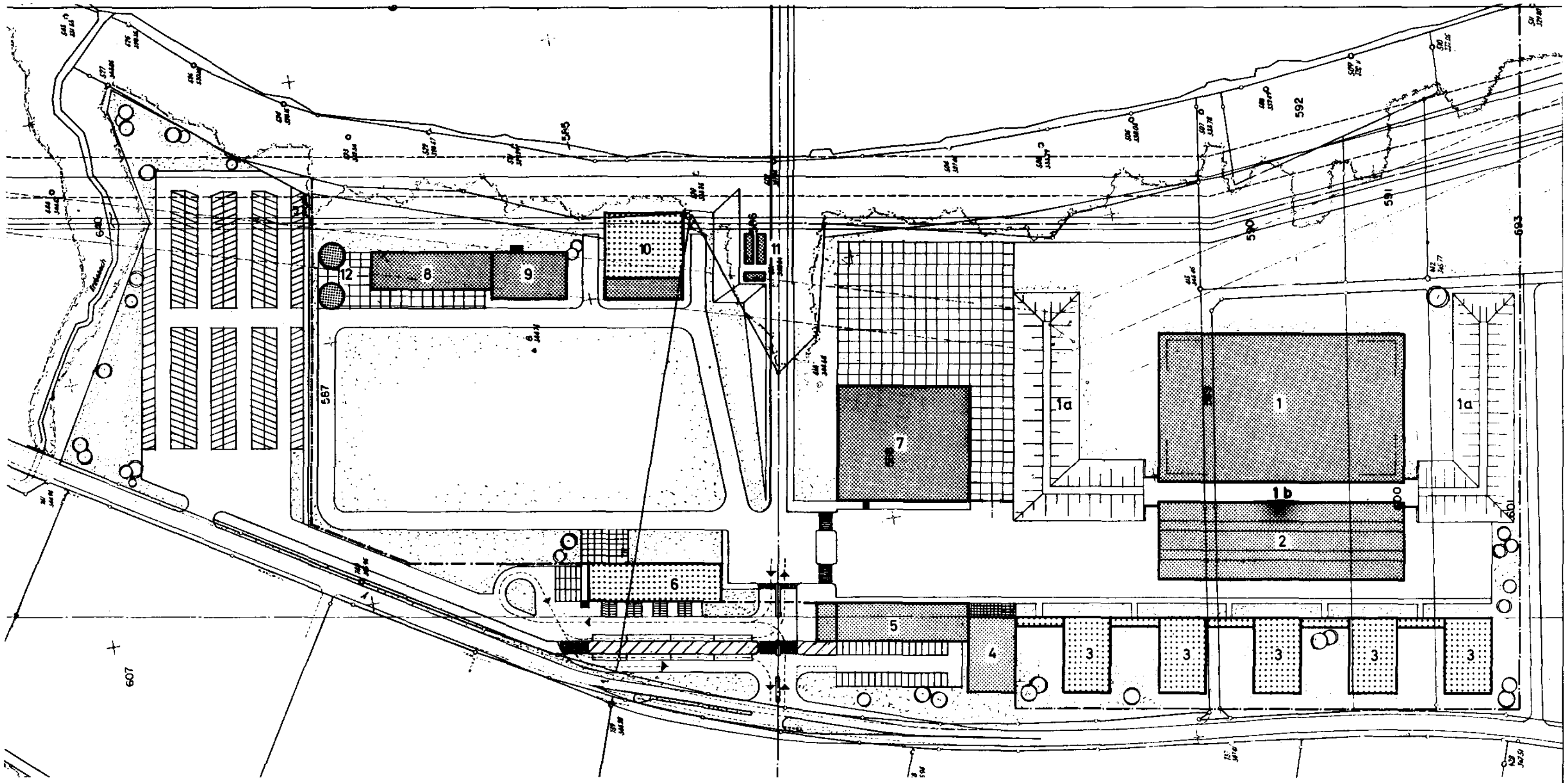
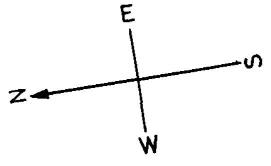


Figure 19.

500 MeV ACCELERATOR SITE PLAN (ETH ZURICH)

1	MAIN HALL, ACCELERATOR & EXPERIMENTS
1a,1b	EARTH SHIELDING
2	OPERATIONS BUILDING (CONTROL, POWER, COOLING, COUNTING)
3	FUTURE LABORATORIES
4	AUDITORIUM
5	OFFICES
6	FUTURE STORES BUILDING
7	WORKSHOPS & ASSEMBLY
8	SERVICE BUILDING
9	HEATING PLANT
10	TRANSFORMER STATION
11	WATER TREATMENT PLANT
12	OIL TANKS



M. 1:2000

DISCUSSION

BLOSSER: Do you have any plans for trying to provide an optional fm mode so that you could stack beams without an internal target, and dump them all at once?

BLASER: We don't think the stacked beam could be used inside the machine, except with this absorbing target. We did not investigate it, but I do not see how we could have enough fm at the end to keep the beam from going out. You would have destroyed the phase, and that looks rather difficult.

Possibly an internal target providing such an absorption may be used with the resonance extraction system to produce a coherent amplitude, so that the beam could go into the resonant extraction; at $\nu_r = 3/2$ you need an amplitude to build it up rapidly.

KHOE: How do you adjust the phases of the bunches, from one cyclotron to the other?

BLASER: The question is still open. The main machine is working on the sixth harmonic, with the six bunches around, and the phase will probably be rather narrow, but there is no hope of making a single-turn extraction. We think the extraction would be helped by keeping the phase narrow, and are considering, therefore, for the injector machine to have some axial injection with bunching, to get the narrow phase.

LIVINGSTON: Could you tell us about the schedule you have in mind for this project, and maybe a word about the cost?

BLASER: We feel, at the moment, it is reasonable to talk about five to six years from now. It may depend on some technical results in the way of development, and it may depend on how much time we need to build up a really efficient group. We have still too few people, because we were starting from zero.

The budget is now $21,000,000, for both the machines and the buildings. Depending on what you count in the building, or in the machine, like the shielding, and cooling systems, it may be about half and half.

RICHARDSON: I assume you are aware of the work of Hopp at UCLA on the $\nu_r = 3/2$ resonance in extraction. The difficulty is, of course, that the resonance is slow building up. You could use it on the 420-MeV extraction, but it might be more difficult to do on the way down, when you must necessarily be out of the isochronous condition.

BLASER: This extraction is, in fact, quite difficult. The buildup can be quite fast, I think, because we will have an initial amplitude (this we may produce by absorbers) and, also, we are in much better shape than other machines, because we can place the bumps in field-free regions. We can have very strong bumps; we have a very narrow gap, so we can build up the bump. The first calculations have shown that after about six to ten turns we should have an amplitude of about 10 cm. It is quite fast, in spite of the half-integral resonance.

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