PROPOSAL FOR A 500 MeV ISOCHRONOUS CYCLOTRON WITH RING MAGNET

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The goal of our studies was to find an accelerator suited for efficient production of high-quality beams of π and μ mesons at intermediate energies. Flexibility in the experimental use, low capital costs and low operating costs (low power consumption) were among our highest concerns. An isochronous proton cyclotron promised best to answer our requirements. In the layout of such a machine we had to aim for :

1. An energy well above the pion production threshold, if possible above 450 MeV.
2. External beam intensities of several tens of μA; a high quality of the external beam.
3. An extraction rate higher than 50% of the beam accelerated to the final energy; minimization of the beam loss during acceleration.
4. A beam pulse repetition rate just within the resolution capabilities of modern electronic equipment (larger than 50 Mc/s).
5. A machine construction which makes maintenance and overhaul possible, especially in view of the activation after a long period of operation.
6. Reliability of operation.

At first, a 6-sector spiral-ridge cyclotron of more conventional design was considered[1)]. Detailed investigations showed however, that with this type of machine it would be difficult to obtain energies beyond 450 MeV. Also the efficient extraction of the beam, the access to vital machine parts (as for instance the accelerating system and the deflection system) and other accelerator engineering problems, were rather difficult to solve.

A 8-fold geometry, as successfully checked in the Oak Ridge Eelctron Analogue[2)], was more promising for obtaining energies beyond 450 MeV. The radial 3/2-resonance, being a machine resonance in the 6-fold geometry, appears as an imperfection resonance in an 8-sector arrangement. It can furthermore be shifted to an energy above 500 MeV by proper choice of the field parameters.

As a figure of merit for the extraction rate achievable in an isochronous cyclotron, we considered the physical radial gain per turn measured in units of the effective magnet gap. A high energy gain per revolution, and a relatively low magnetic field produced by small-gap magnets were believed to be of advantage for beam extraction. An arrangement of separated magnet sectors, leaving space for high-voltage accelerating cavities in the iron-free sections, offered an increase of the figure of merit by at least a factor of 10, compared to an isochronous cyclotron of conventional design. In order to keep the power consumption of the accelerating cavities small, the free sections must be so wide that the magnetic field is zero over a wide azimuthal range in the valleys. The physical size of the accelerating cavities also requires that this type of isochronous acceleration is limited to a radial range approximately $0.3 \leqq R \leqq 0.8$ (cyclotron units). Hence, the accelerator becomes a ring into which the beam has to be injected at $\beta \gtrsim 0.3$.

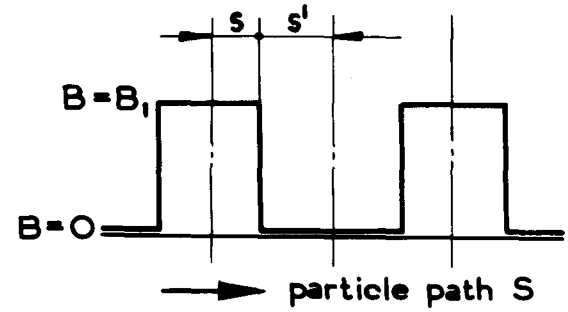

Fig. 1 Hard edge flutter function.

For the pre-acceleration is proposed another isochronous cyclotron. It permits a macroscopic duty factor of unity and provides the required beam pulse sequence, when operated with a 2- or 3-dee system on a sub-harmonic of the cyclotron frequency. Recent experiences with extracted beams from isochronous cyclotrons[3)] gave encouragement for further investigation of such a two-stage accelerator.

<u>Beam Dynamics</u>

For the first layout studies the magnetic field met by a particle passing through a sector was assumed to show a "hard edge" at the magnet edge while remaining zero outside the magnet and constant = B_1 on the path through the magnet gap (Fig. 1). To maintain isochronism the hill field B_1 must change in a certain fashion from revolution to revolution, depending on the change of the azimuthal width of the magnets. It can be shown that in this case the flutter factor $F^2 = \langle B^2 \rangle / \langle B \rangle^2 - 1$ can be expressed by

$$F^2 = \frac{A}{\gamma} - 1 = \frac{s'}{s}, \qquad (1)$$

with $A = B_1/B_0$ (B_0 = centre isochronous field).
From the axial focusing equation

$$Q_z^2 = 1 - \gamma^2 + \frac{N^2}{N^2 - 1} F^2 (1 + 2\,\mathrm{tg}^2 \xi) + \dots\dots\dots,$$

where $\gamma = \frac{T}{E_0} + 1$, N is the No of sectors, ξ the spiral angle, and Q_z the axial betaron frequency follows

$$\frac{N^2}{N^2 - 1} (1 + 2\,\mathrm{tg}^2 \xi) \approx \frac{Q_z^2 + (\gamma^2 - 1) - \dots}{(A/\gamma) - 1} \qquad (2)$$

Fig. 2 is a working diagram which gives numerator and denominator of Eq. (2) as functions of γ, with Q_z and $A = B_1/B_0$ as parameters. For an easier comparison the relationship between γ, the kinetic energy T, and the equivalent radius (in cyclotron units) is also shown. The diagram illustrates the relationship between radial shape of the hill field, the flutter factor and spiral angle necessary to obtain a certain

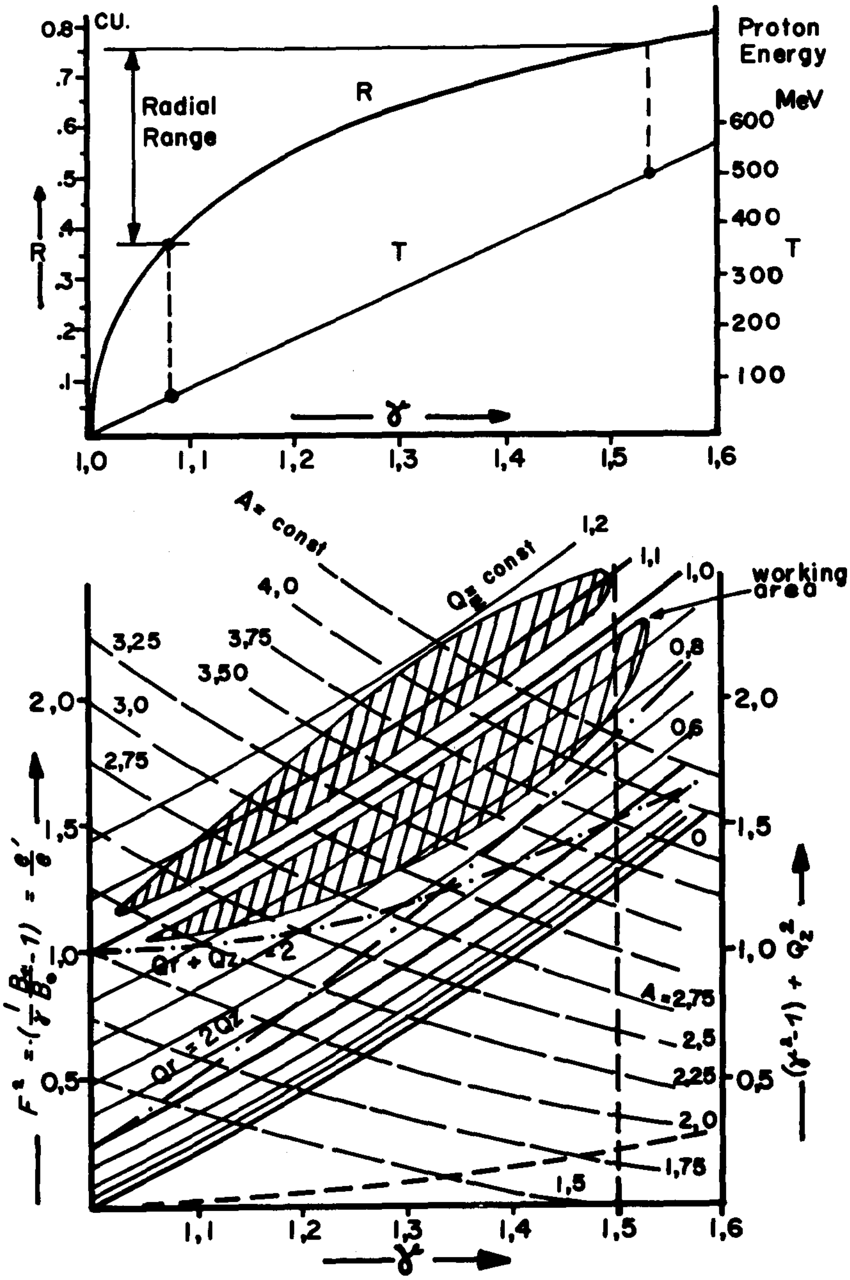

Fig. 2 Working graph for the layout of an 8-sector hard-edge isochronous field. Equivalent radius, flutter factor and spiral-angle defining function $(\gamma^2 - 1) + Q_z^2$ vs. $\gamma = \frac{T}{E_0} + 1$.

working path of Q_z. Since Q_r remains very close to γ one can also reconstruct the Q_z, Q_r diagram in this working graph, and mark the main resonance and the beam stability regions.

It can now be derived from this graph that in order a) to make the field free sections wide enough for placing the cavities between the magnets, b) to shift the working path into a region where no serious resonance is crossed, and c) to keep the

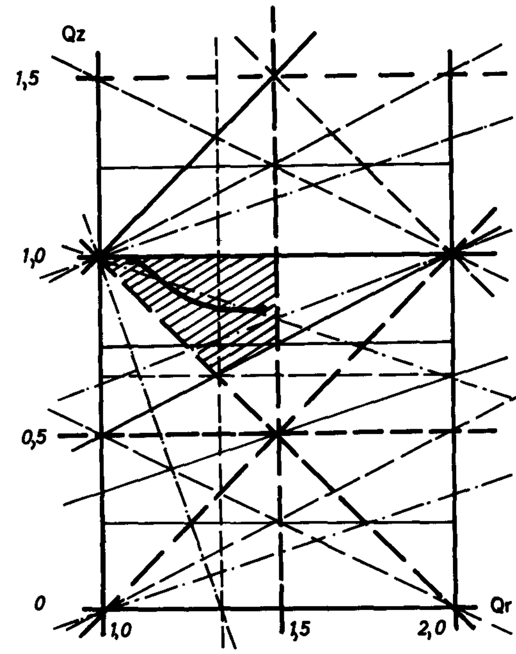

Fig. 3 Q_r, Q_z diagram for an 8-fold sector geometry showing also higher order coupling resonances. Proposed working area with computed working path for the sector geomatry under consideration.

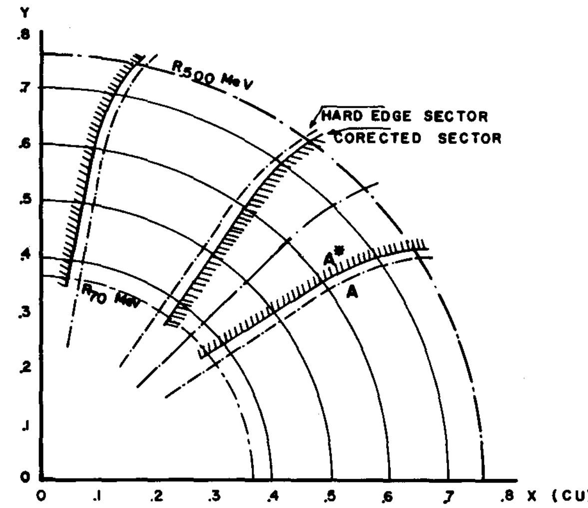

Fig. 4 Hard edge sector geometry and sector shape after correction taking account of the fringe field of the magnets.

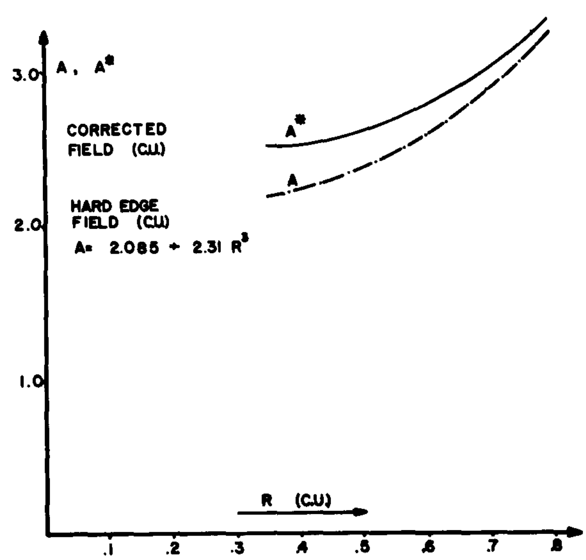

Fig. 5 Radial increase of the field in a magnet section, curve A shows the hard edge case, and A* the case corrected for the fringe field of the magnets.

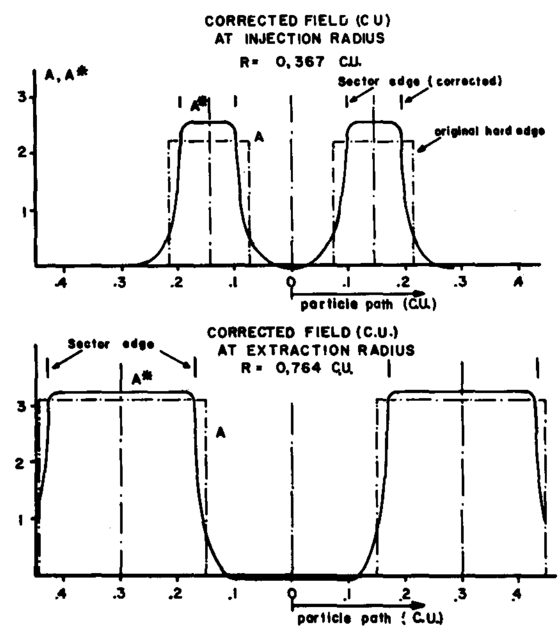

Fig. 6 Field configuration along a particle path at the injection radius and at the extraction radius.

hill field within technically feasible limits, and the spiral angle small enough, one has to 1) start operation beyond 50-70 MeV, 2) preferably start with a flutter factor beyond 1.0 and with very little or no spiral angle, and 3) shift the working region for Q_z from the commonly used range below $Q_z = 0.3$ into a region above $Q_z = 0.7$.

There is still a large freedom of choice for the sector form and the radial dependance of the hill field providing isochronism as well as proper focusing. Several geometries were computed with the aid of an IBM 709-programme by Vogt-Nilsen[4]. This programme is based on multiplication of transfer matrices for magnet sections with slanted edges, and takes account of the linear betatron motion. It was found that the energy where Q_r reaches a certain value can be affected slightly by the radial rate of change of the flutter. We succeeded in finding a field geometry that permitted use of the radial 3/2-resonance for beam extraction slightly beyond 500 MeV. Fig. 3 shows the working path in the Q_r, Q_z diagram, Fig. 4 the required sector geometry and Fig. 5 the radial shpae of the sector field for this case.

Corrections were applied to this hard-edge field sector to take into account deviations from the hard-edge case due to the magnetic fringe field. The shape of the fringe field expected was measured in a 1/12-scale magnet model. The corrections are such that the average field and the average squared field of the "hard-edge" and the "real" field are the same at all radii thus leaving the flutter unchanged. Fig. 6 illustrates the changes in the field shape as expected at the injection radius and the extraction radius.

General cyclotron orbit codes, developed at the CERN MSC Division will be used in combination with a 1/7-scale model to find the proper magnet pole shape. The effects of the resonances $Q_z = 1$ and $Q_z + Q_r = 2$ which are close to the working path, especially at the beginning of acceleration, are being studied at present.

Beam Injection into the Ring Accelerator

We propose to inject the beam onto an equilibrium orbit. The large expected radial gain per revolution (approx. 1.5 cm at the inner radius) makes it possible to use an electrostatic or magnetic injection channel with a septum. Fig. 7 shows schematically the situation at the injection radius.

Only the fraction of the beam phase space best suited for transmission through the accelerator and its beam extraction device should be injected. Which fraction of the beam one should accept from the injector will depend largely on the extraction device and the internal beam properties of the machine. According to recent experience with sector-focused cyclotrons, it is almost certain that a fixed-energy AVF cyclotron for approximately 70 MeV protons can be especially designed for extraction of a beam with high quality. Using data from computations of the external beam quality of the Berkeley 88-inch cyclotron[5] an external beam

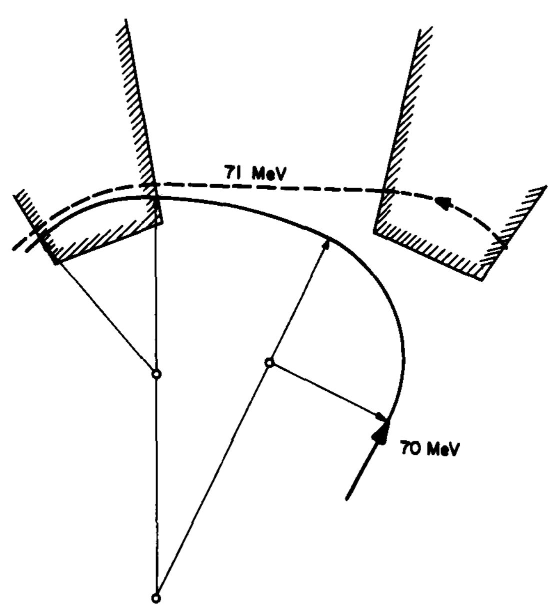

Fig. 7 Beam injection (schematic).

transfer efficiency of larger than 50% was estimated. With an extraction rate of order 30 - 40% at the injector cyclotron, a total beam transfer efficiency of 15 - 20% seems to be achievable.

A method to avoid non-linear beam-distorting effects due to passage through the cyclotron fringe field is to use negative hydrogen ions in the injector. With an internal gas target a large fraction of the H^- ions could be stripped to neutrals, which would pass the fringe field with very good optical quality. With a second, external target the final conversion to protons could be achieved.

Beam Extraction from the Ring Accelerator

In a typical case with an energy gain of approximately 1 MeV per turn, an average magnetic field of 7.5 kG and a gap of 8 cm, the radial turn separation at the extraction radius is on the order of 3 mm, increasing to 6 - 10 mm at the field turn-over. The incoherent radial beam amplitude is expected to remain of order $\pm$ 3 mm, the axial amplitude $\pm$ 5 mm. These features make extraction of a very large fraction of the internal high energy beam possible. The radial 3/2 imperfection resonance can be used successfully with localised field bumps placed at proper azimuths. Preliminary computations for a simplified model with two field bumps separated by 60° in azimuth, one increasing and the other decreasing quadratically with radius show a very rapid growth of the radial amplitudes. The arrangement of a properly designed magnetic channel with low axial aperture is possible in one of the field free sections.

Accelerator Layout

The layout studies were based on the following technical and physical requirements :

1) To make the C-type sector magnets economical, the hill field should not exceed 19 - 20 kG.

2) In order to retain the possibility of accelerating negative hydrogen ions in the injector cyclotron, its maximum hill fields should not exceed 20 kG. (Otherwise the Lorentz-dissociation would become too large[6]).

3) The pulse repetition rate should be in the order of 50 mc/s or higher.

4) In order to keep the costs of the high energy ring accelerator low, the radial range of this device should be kept small. Consequently, the injection energy should be just as high as technically tolerable for pre-acceleration, beam extraction from the injector, and beam injection into the ring.

5) The ring accelerator should be designed for maintenance without exposing personnel to a high background radiation.

We arrived at a solution as shown schematically in Fig. 8. A three-sector spiral-ridge cyclotron, with three dees placed in the valleys and operating on the third sub-harmonic of the cyclotron frequency, delivers a 70 MeV proton beam with a pulse sequence of 60 Mc/s. This beam is transferred into the isochronous ring accelerator with its 8 separate, small-gap C-magnets. The injection radius of the ring accelerator is 2.3 m, the extraction radius 4.9. The main components for the ring accelerator are

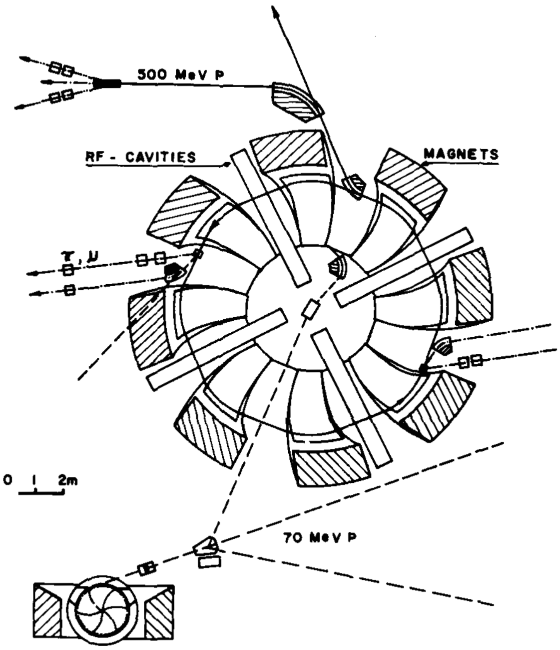

Fig. 8 Schematic layout of the isochronous ring accelerator with injector.

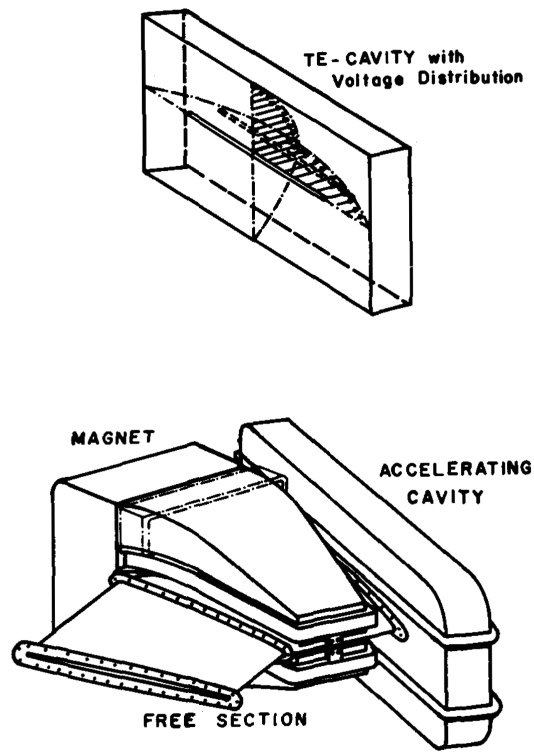

Fig. 9 Schematic sketch of the main components of the isochronous ring accelerator.

sketched in Fig. 9. Four symmetrically arranged TE-cavities, excited at 60 Mc/s on the H_{101} -mode provide an energy gain of 1 MeV or more per revolution. Field and frequency of both machines are fixed. The RF systems are driven by a highly stable master oscillator.

The remaining free sections provide a number of advantages : Magnetic channels for beam injection and extraction can be placed so that they become accessible and removable when activated to an intolerable level. The field perturbations necessary at extraction for excitation of large amplitudes can easily be positioned. The use of internal multiple-traversal targets for meson production becomes efficient, since a large fraction of the mesons can be guided away regardless of charge and energy. Several experimentally useful beams can be provided simultaneously. Internal beam collimators to protect accelerator parts from the primary proton beam can be mounted in an exchangeable way. Access for probes and targets to the beam plane is greatly simplified. Outside the vacuum chamber there is space between the magnets for secondary-beam stopping and neutron shielding material.

Technical Features of the Accelerator

The accelerator data of interest are listed in Table I. Fig. 10 shows a plan view of the preliminary technical layout of the isochronous ring accelerator. The main components of the accelerator - the magnets, RF cavities and the sections of the vacuum chamber - are largely independent units. We aim for a standard design of these

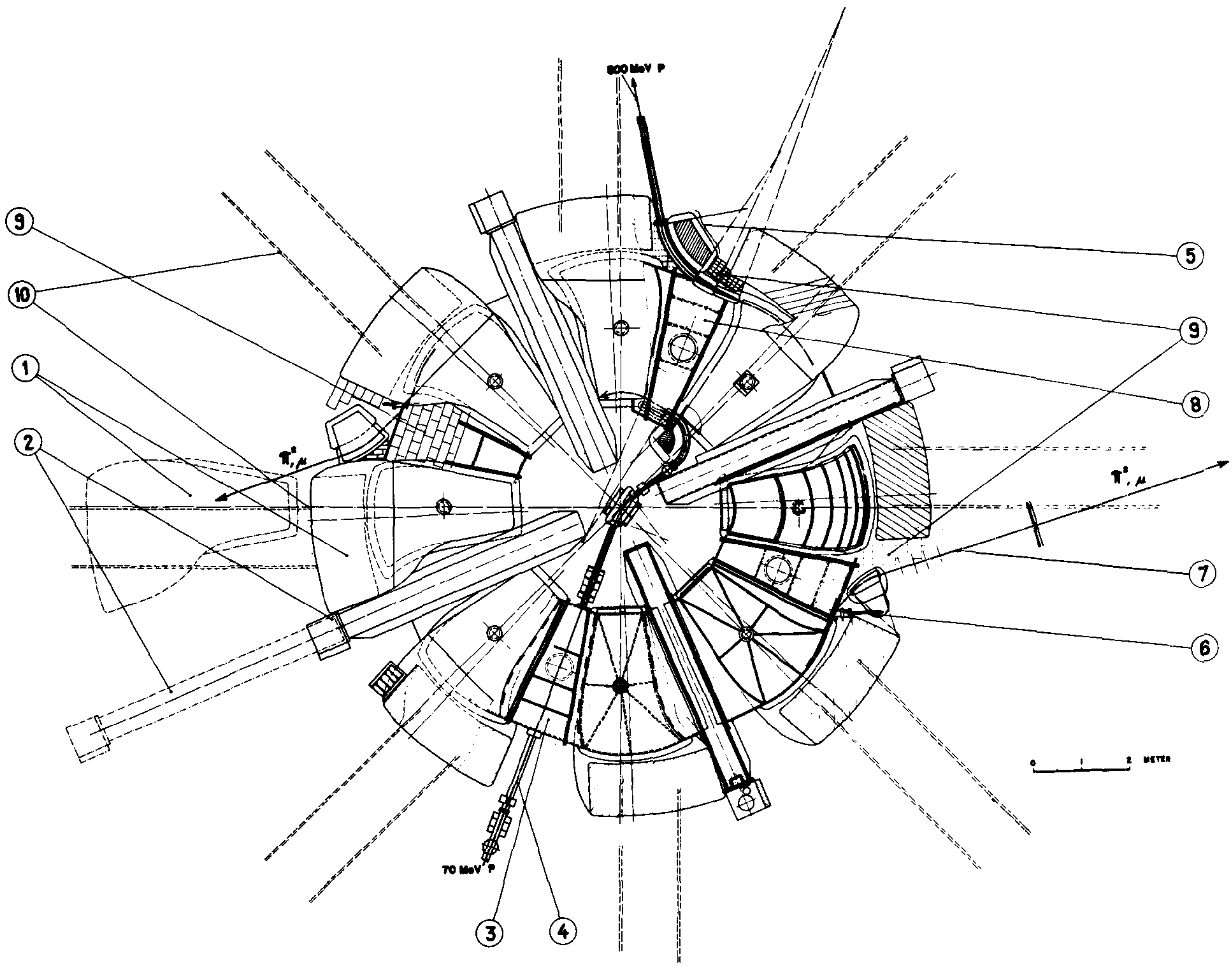

Fig 10 Isochronous ring accelerator. Plan view with sections.
1) Sector magnets (cast magnetic steel), mounted on tracks, three point support, removable in radial direction, precision adjustment possible. 2) TE cavities excited at the H_{101}-mode, quality factor 20-30 000, plug-in units, exhangeable. 3) Vacuum chamber; toroidal flat tube with rectangular cross-section, consisting of different azimuthal sections which are flanged together (metal gaskets). Reinforcements on the outside. Vacuum requirements : 3×10^{-5} Torr. 4) Beam injection system. 5) Beam deflector. 6) Internal meson production target (multiple traversal target). 7) Meson beam guiding system. 8) Internal beam collimators (graphite). 9) Neutron shielding (heavy antimagnetic material, such as Baryte concrete or Basalt). 10) Supporting tracks for magnets.

main parts, so that they will be replaceable if necessary. The accelerating cavities are planned to be "plug-in units", replaceable when voltage holding becomes difficult due to contamination, or when activation rises to an intolerable level.

The eight identical magnets will be tested and shimmed to a high degree of accuracy before the final assembly. Thus we expect to avoid very expensive precision machining of the heaviest parts. We plan to have small trimming coils on each magnet sector. The power consumption is rather low, since the gap is small and we believe that we can shim each section so carefully that a total of range of ± 30 to 50 gauss for each coil should be sufficient for adjustment.

For the vacuum chamber, we propose a flat toroidal tube of stainless steel with flange connections (metal gaskets) between the separate sections, and reinforcements where space is available. The main coils, and also the low-power trimming coils should remain outside the vacuum. There are some difficult engineering problems to be solved, if we are to avoid corner seals or seals around the pole plates, but in view of the reliability requirements and maintenance problems it seems worth while to increase the effort on this side. Some reasonable solutions have already been proposed. The machine components have not yet been optimized with respect to costs, performance and reliability.

The cost of the ring accelerator described in Table I and Fig. 10 was estimated to 20 - 22 million SFrs, including 3 - 4 million SFrs development cost. The cost of the injector cyclotron has not been estimated. A total construction time of 5 - 6 years will be required.

Table I

Data for Proposed 500 MeV ETH Accelerator

1. Injector Cyclotron

Final energy	70 MeV
Centre isochronous field	13 kG
Maximum hill field	20 kG
Maximum orbit radius	0.89 m
Magnet gap	≈ 7 cm
No of sectors	3
Maximum spiral angle	≈ 40°
Cyclotron frequency	20 Mc/s
Pulse sequence	60 Mc/s
Pulse length	> 0.5 - 0.7 ns
Beam intensity (internal, depending on extraction rate)	100 - 500 μA
Beam extracted (depending on quality)	50 - 200 μA

Beam extraction : either electrostatic or with magnetic channel.

Requirements for beam to be injected into the ring accelerator :

Energy spread $\Delta E/E$		- 0.4 to + 0.2%
Spot size divergence (full width, full angle)		
	radial :	4.4 mrad cm
	axial :	3.2 mrad cm
Luminosity		> 7 A/cm^2 sterad

Magnet :	H-yoke	
	Pole diameter	1.92 m
	Weight	~ 200 t

RF system :	3 dees in valleys	
	Frequency	60 Mc/s
	Voltage (peak/ground)	45 kV
	Excitation driven system	

2. <u>Isochronous Ring Accelerator</u>

Final energy	$\approx$ 516 MeV
Injection energy	70 MeV
Centre isochronous field	4.88 kG
Hard-edge sector field	10.7 - 15.4 kG
Injection radius	2.3 m
Extraction radius	4.9 m
Magnet gap	10-7 cm
Iron-free azimuth/magnet azimuth	$\approx$ 1.05
No of sectors	8
Maximum spiral angle	25°
Radial betatron frequency Q_r	1.05 - 1.5
Vertical betatron frequency Q_z	0.98 - 0.84
Cyclotron frequency	7.5 Mc/s
Pulse sequence	60 Mc/s
Pulse length	$\gtrapprox$ 0.5 ns
Beam intensity (internal)	30 - 100 μA

Amplitudes at injection radius $\pm$ 0.5 cm radial, $\pm$ 0.75 cm axial
Amplitudes at extraction radius < $\pm$ 0.3 cm radial, < $\pm$ 0.5 cm axial
(with damping)

Luminosity at injection radius (required)	3 - 8 A/cm^2 sterad
Luminosity at extraction radius	$\lesssim$ 60 A/cm^2 sterad
Output energy spread	$\approx$ $\pm$ 1 MeV
Average energy gain/revolution	1 MeV
Radial gain per turn at injection radius	1.5 cm
Radial gain per turn at extraction radius	0.3 cm
Beam injection	on equilibrium orbit by electrostatic or magnetic channel
Beam extraction	regenerative with magnetic channel probably using the 3/2 imperfection resonance

<u>Magnets</u> (C-type, 8 units)

Steel weight per unit	174 t
total	1400 t

Copper weight per unit	7.3 t
total	58 t
Electric power per unit	47 kW
total	380 kW
Trimming coils (on pole plates)	7 pairs per unit
Electric power per pair	30 - 40 watt
total	2.1 kW

RF system (Rectangular TE cavities, 4 units)

Frequency	60 Mc/s
Voltage (peak)	350 kV
Skin power loss (per unit)	≈ 62 kW
Beam load (per unit)	< 12 kW
Total power consumption	290 kW

Vacuum system (Flat toroidal tube with exchangeable sections, metal gaskets)

4 Oil diffusion pumps with low temperature baffles	8000 l/s each (unbaffled)
4 Ion-getter pumps (on RF cavities)	1000 l/s each

Special provisions to reduce induced activities and shielding problems

Internal beam collimators, carbon, exchangeable (mainly in free sections).

External neutron shielding material in free sections.

RF cavities and parts of vacuum chamber, replaceable.

Injection and extraction channel, replaceable.

Beam defining collimators in injection system.

Remote handling of internal targets.

Flanges and connections easily rémovable.

Gross dimensions

Outer diameter	13 m
Height above beam plane	1.8 m
Total weight	1600 t
Total power (magnets + RF + vacuum)	≈ 950 kVA

References

1. J.P. Blεser and K. Steimel, Nucl. Instr. and Meth. 18-19, 417 (1962).
2. J.A. Martin and J.E. Mann, Nucl. Instr. and Meth. 18-19, 461 (1962).
3. E. Kelly and H. Grunder (Private communication).
4. N. Vogt-Nilsen, CERN (Private communication).
5. A.A. Garren and D.L. Judd, Nucl. Instr. and Meth. 18-19, 525 (1962).
6. D.L. Judd, Nucl. Instr. and Meth. 18-19, 70 (1962).

DISCUSSION

RICHARDSON : You mentioned being able to vary the energy for the 3/2 resonance over a range. Are you planning to make use of that or was that just an observation?

WILLAX : Right now we have just started the computation of this, so I do not know in what range we can vary the energy by changing the rate of change of flutter by using the trimming coils