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Design Study for a Large-orbit Electron Synchrotron

The design concepts for large-orbit electron synchrotrons proposed by the staff of the Cambridge Electron Accelerator (CEA-84, CEA-88) and also reported in the Brookhaven "Design Study for a 300-1000 BeV Accelerator" - Aug. 28, 1961, have been modified to fit the orbit dimensions of the 150-GeV and 300-GeV proton synchrotrons which are being studied by the CERN Accelerator Research Division. The electron energies which can be attained in these orbits within practical power requirements are about 40 GeV and 50 GeV respectively. A table of basic parameters and cost estimates are included in this study, but in a very preliminary form. The cost estimates are for the machine costs only and represent the additional costs in the event that an electron machine were to be built within the tunnels provided for a proton machine and sharing the use of facilities and power. Costs for a separate installation would be larger by about a factor of two.

Magnet

A large-orbit electron synchrotron is limited in energy by the radiation loss from the orbiting electrons, which requires a very high-power radiofrequency accelerating system. On the other hand, AG magnets are small and magnetic field is low, so a relatively large fraction of the orbit can be assigned to rf acceleration. The optimum division of the orbit between magnet and rf acceleration, to minimize rf power requirements, is in the ratio of 2 : 1 as shown by J. R. Rees (CEA-88).

The FODO assembly of AG magnet sectors, with equal-length straight sections (O) in which rf units are located, provides the large momentum compaction desired to accommodate the momentum spread of a linac injector. Betatron frequency can be tuned by radial positioning of the F and D sectors, which removes the need for quadrupole lenses. Rf units are located in regions where both radial and vertical oscillation envelopes (β-factors) are reduced below their maximum values, which reduces aperture requirements for the rf units.

Some long straight sections are provided, for injection, targets and emergent beams, with total lengths equal to those proposed for the CERN proton synchrotrons. Quadrupole matching lenses will be provided, as proposed by Collins (CEA-85), to minimize the effect on the AG oscillation amplitudes.

The magnet aperture is chosen to accept a momentum spread of ± 0.5%, which is physically small due to the momentum compaction of the strong focusing system. The aperture provides space for orbit distortions in both transverse coordinates which would result from local misalignment errors of ± 0.01 cm (rms), and from the magnetic irregularities to be expected at injection. Betatron amplitudes will be quite small, due to the expected small emittance of the linac at injection energy.

Peak magnetic fields are low, due to the large orbit, allowing the use of a magnetic return circuit of small cross-section and also coils of small cross-section, so the magnet will be even smaller than the Cambridge magnet. It seems suitable to encase the entire magnet within a soft-steel pipe, to shield the magnet from external stray magnetic fields. This outer casing can be made the vacuum jacket, eliminating the need for a laminated chamber between pole faces. The outer pipe casing may also be designed to provide the structural support required to maintain alignment within each magnet unit.

The magnet will be powered with full-biased ac, as for the CEA. A cycling rate of 60 cps is chosen to avoid build-up of radiation-induced oscillations and loss of beam. The magnet structure will be laminated and the coils formed of stranded cable to minimize eddy currents. Power can be supplied from a resonant system of capacitors and inductors, as in the Cambridge machine (CEA-81).

Radiofrequency

An rf accelerating system of high efficiency can be provided by using many identical units of diaphram-loaded waveguide of the type used for linear accelerators, at as high a frequency as possible within the requirements of aperture needed to accommodate the beam, and in units long enough to make efficient use of rf power. The frequency chosen is 1000 Mc/sec. The iris apertures can be oval holes of about 8 cm x 3 cm in a 25 cm diameter guide. Each rf unit will be essentially a short linear accelerator driven by a single power tube. Individual units will be tuned to the same frequency and driven from a common master oscillator, with individual phases derived from the bunched electron beam coming from the injector linac.

Injection

The injector linac will operate at the same frequency as the synchrotron rf, probably using similar waveguide units (with circular apertures), with the units pulse-powered to produce beam pulses adequate for one-turn injection. A pulsed magnetic inflector in a long straight section is used to direct the linac beam into the orbit and then will be pulsed off in a time short compared with the orbital period. Injection energy is chosen for an injection field B_o of 50 gauss. This is higher than the 30-gauss field used successfully in the Cambridge accelerator. At 50 gauss the energy required for the 300-GeV orbit is 1.0 GeV, which is within present capabilities.

It seems desirable to provide for acceleration of positrons as well as electrons. An initial linac unit of very high intensity (1 A) and modest energy (30 MeV) can produce positrons from a radiator in the beam, which will then be accelerated to injection energy in the linac. The polarity of magnet excitation would be reversed. Estimates suggest a conversion efficency of about 10^{-4}.

Vacuum System

Preliminary design concepts for the magnets suggest the desirability of encasing the entire laminated magnet within an external steel pipe, which serves as a vacuum envelope. The rf waveguide units also provide their own vacuum casings. A large number of low speed pumps will be attached at the junctions between magnet and rf units, and provided with suitable roughing pumps. Electronic or molecular pumps will be used, to avoid the necessity for refrigerant cooling.

Intensities:

Beam intensity will probably be limited by beam loading of the rf system. Space charge does not seem to be a limitation in this large orbit. Assuming full performance of all components the maximum intensities can be estimated. For a 100-mA output beam from the linac about 50 mA will be within the momentum-spread of the synchrotron and, if captured in synchronous orbits, would result in 4×10^{12} and 8×10^{12} electrons per pulse for the two sizes of orbit. At 60 cps the time average currents would be 2.4×10^{14} and 4.8×10^{14} electrons per second, respectively, or 50 and 100 microamperes. Beam loading and other synchronous capture limitations would probably reduce actual intensities well below these values.

Problems Needing Further Study

1. The first-order optimum of 2 : 1 for length of magnet to length of rf accelerator may be modified on further study of the effect of beam requirements on the power balance.

2. The mechanical and structural design of the magnet units requires study to minimize fabricating costs and to reduce errors in alignment.

3. Further study of space requirements for coil-ends, vacuum ports, pick-up electrodes and other auxiliary devices is needed to determine the length of short straight sections.

4. The proposed oval aperture (8 cm x 3 cm) in the iris diaphragms for the rf waveguide units must be analyzed for possible parasitic mode problems. The results may require a decrease in the proposed 1000 Mc/sec frequency.

5. The availability of power triodes and klystrons as power sources for the rf system and the linac may influence choice of frequency and unit size.

6. Problems of phasing the hundreds of rf waveguide units around the orbit must be studied to minimize phase errors. Beam-loading effects on the rf units, which depend on beam current, must also be analyzed, and a system developed to compensate for the beam loading.

7. A beam ejection system should be devised.

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References

CEA-81	"The Cambridge Electron Accelerator" (Aug., 1960).
CEA-84	"A Radiofrequency System for a 50-Bev Electron Synchrotron" - J. R. Rees (July, 1961)
CEA-86	"Long Straight Sections for AG Synchrotrons" - T. L. Collins (July, 1961)
CEA-88	"Large Orbit Electron Synchrotron" - T. L. Collins, M. S. Livingston, J. R. Rees and H. S. Snyder (July, 1961)

"Design Study for a 300-1000 Bev Accelerator" - Brookhaven National Lab. (Aug. 28, 1961)

CERN: AR/Int. SG/62-13	"Tentative Parameters for a 300-GeV AGS" L. Resegotti (Oct. 2, 1962)
CERN: AR/Int. SG/62-15	"Tentative Parameters for a 150-GeV AGS" L. Resegotti and W. Schnell (Nov. 23, 1962)

CERN
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Parameters for Large Orbit Electron Synchrotron

(orbit sizes for CERN 150/300 GeV P.S. designs)

	(150):	(300):	
Orbit Dimensions:			
Electron energy	40.	50.	GeV
Machine radius, R	600.	1200.	m
Machine circum., total	3770.	7541.	m
Long st. sections, total	162.	648.	m
Accel. circum.	3618.	6893.	m
Assigned to magnets (0.6)	2170.	4136.	m
Assigned to rf (0.3)	1085.	2068.	m
Magnetic rad. curv., ρ	346.	658.	m
Max. field at max. en.	3740.	2500.	gauss
Acceleration Parameters:			
Cyclic repetition rate	60.	60.	c/sec
Mag. field at injection, B_o	50.	50.	gauss
Injection energy at B_o	0.54	1.0	GeV
Orbital period	12.6	25.2	microsec
Accel. time (B_o to B_m)	7.70	7.60	millisec
No. revol./accel. cycle	610.	300.	turns
Rate of accel. at inject	30.	93.	MeV/turn
No. turns/synch. phase oscill. at inject.	3.3	2.8	
Max. rate of accel. (at $\frac{1}{2}B_m$)	129.	334.	MeV/turn
Max. rate of radiation loss (at B_m)	660.	840.	MeV/turn

	(150):	(300):	
A.G. Magnet (FODO assembly)			
No. of AG periods, N	114.	156.	
No. of long st. sections	6.	12.	
Mag. length/period	19.0	26.5	m
No. mag. half-units (4/period)	456.	624.	
Length of half-unit (straight)	4.76	6.62	m
Aperture: gap at central orbit	3.8	3.8	cm
Width of uniform field	8.6	8.6	cm
Charac. length, $x_o = B/\frac{dB}{dr}$	21.6	21.9	cm
AG phase angle/period	1.86	1.88	rad
No. betatron waves/turn ν	33.4	46.7	
Momentum compaction factor	7.35	7.46	$\times 10^{-4}$
Magnet Power			
Ampere turns for B_m	12.5	8.4	$\times 10^3$ NI
NI_{rms} for sinusoidal excit'n	7.1	4.7	$\times 10^3$ NI
Copper coil cross-section	50.	50.	cm^2
I^2R power/half-unit	1.54	1.30	kW
Eddy current and mag. losses	0.46	0.30	kW
Power in magnet/half-unit	2.0	1.6	kW
Total power for magnets	910.	1000.	kW
Circuit losses (est.)	910.	1000.	kW
Total power requirement	1.8	2.0	MW

	(150):	(300):	
Radiofrequency			
Frequency	1000.	1000.	Mc/sec
No. of rf units	222.	300.	
Length of rf unit	4.90	6.87	m
Waveguide diam. (approx.)	25.	25.	cm
Iris aperture (approx.)	8 x 3	8 x 3	cm x cm
Shunt R/m (est.)	28.	28.	megohm/m
Shunt R/unit	137.	192.	megohm/m
Peak rf volts/unit	3.45	3.25	x 10^6 V
Peak rf power/unit (Cu)	87.	55.	kW
Av. power/unit (Cu)	14.7	9.3	kW
Beam power/unit (.4 Cu)	5.9	3.7	kW
Total av. rf power/unit	20.6	13.0	kW
Input ac/unit power supply	68.	43.	kW
Total ac power	15.2	13.	MW
Linac (same freq. as rf units as synch.)			
Energy	0.54	1.0	GeV
Pulse length (1 turn + 4 μs)	17.	30.	microsec
Duty cycle	1.0	1.8	x 10^{-3}
Peak voltage/unit (3 MeV/m)	15.	20.	x 10^6 V
Peak rf power/unit (Cu)	1.75	2.1	MW
rf power/unit (beam)	2.5	2.5	MW
Av. rf power/unit	4.35	8.3	kW
Av. ac/unit power supply	14.4	27.4	kW
No. of units in linac	42.	58.	
Total length of linac	205.	398.	m
Total ac power	0.6	1.6	MW

Cost Estimates

Magnet a \$1,800/m	3.9	7.5	x 10^6 \$
Reson. Power a \$600/kW av	1.1	1.2	"
Rf units a \$3,400/m	3.7	7.0	"
rf power a \$1,500/kW av	6.8	5.9	"
dc power a \$200/kW ac	3.0	2.6	"
Linac units a \$3,400/m	1.4	2.0	"
rf power a \$1,500/kW av	2.7	7.2	"
dc power a \$300/kW ac	0.2	0.5	"
Hi-inten linac unit (30 MeV)	0.6	0.6	"
Vacuum system a \$660/m	2.5	5.0	"
Auxiliaries and Controls	3.5	5.5	"
Salaries, incl. develop.	5.0	6.0	"
Installation labor	1.2	2.0	"
	35.6	53.0	
Contingency, 20%	7.0	10.6	
Total Machine Cost	42.6	63.6	M.\$
	184	275	M.S.F.

Manpower Estimates (5 yrs)

Professional and engineering	40.	50.	av.no./yr
Supporting staff	120.	150.	"
Total	160.	200.	"