Proceedings of the International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, 1966



# THE SUPER-SOC

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**Abstract**

A new concept in cyclic particle accelerators is described in which time harmonic accelerating fields are produced without recourse to conventional power amplifiers. Instead, the accelerating fields are produced by extracting energy from a bunched beam of particles. In essence the new machine consists of two intimately connected Separated Orbit Cyclotrons, one of which is operated in the decelerating mode. The decelerating particles obtain their energy initially from a D.C. high voltage supply.

## Introduction

The subject of this paper is a new concept in cyclic particle accelerators in which charged particles are accelerated by interaction with another beam of charged particles within a system of cavities. In attempting to reduce the R.F. losses associated with certain types of cyclic particle accelerators, in particular the SOC,[1] the possibility of incorporating the power amplifier systems directly into the several R.F. cavities was examined.[2] Stimulated by this approach and by its limitations a new machine was proposed[3] which incorporated several unusual features.

## Principle

To understand the principles involved it is helpful to consider the mode of operation of an SOC. With reference to figure 1, as charged particles are accelerated in the resonant cavities they are constrained to move in a spiral path by a guiding and focusing magnetic field. The cavities are assumed to be excited in some way and suitably phased so as to maintain synchronous acceleration of the particles. The SOC operates at a fixed frequency and with a fixed magnetic field.

As particles gain energy their speed increases asymptotically to that of light. In an SOC, therefore, with increasing energy, particles spiral to larger radii, approaching asymptotically a limiting radius, $R_\infty$ .

Since the particles gain energy from the electromagnetic fields in the cavities and are accelerated then, conversely, the electromagnetic fields could be produced by deceleration of other charged particles. This concept forms the basis of the new proposal.

Suppose a beam of high energy electrons which have been bunched in space is fed into the machine and guided along a path defined by the $R_\infty$ radius. The phasing of this beam of electrons is arranged so that they are decelerated in passing through the cavities, thereby giving energy to the fields in the cavities. After several such decelerations the electrons will have lost most of their initial energy, and, with a value of β now considerably less than unity, will be unable to maintain synchronism with the periodic structure of the cavities and are therefore discarded. To excite all the cavities in a given machine several

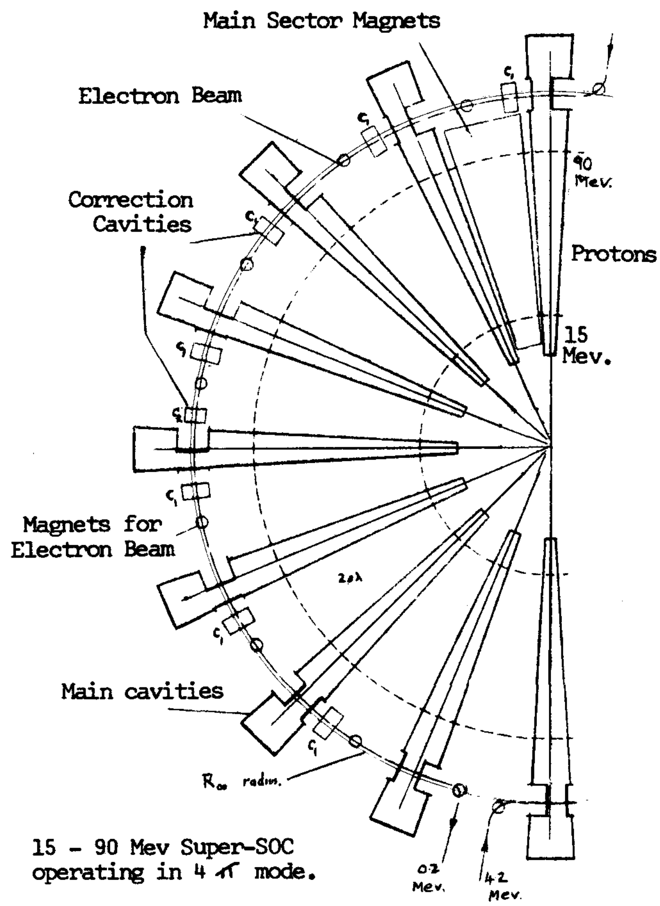


Figure 1. Principle of the Super-SOC

such beams might be required.

## The Electron Beam

Suppose that the secondary beam of electrons is produced in the manner indicated in figure 2. Grid modulation of the beam intensity is preferred within the 'gun' over subsequent cavity modulations, as the phase-range of the electron bunches can be easily

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controlled.

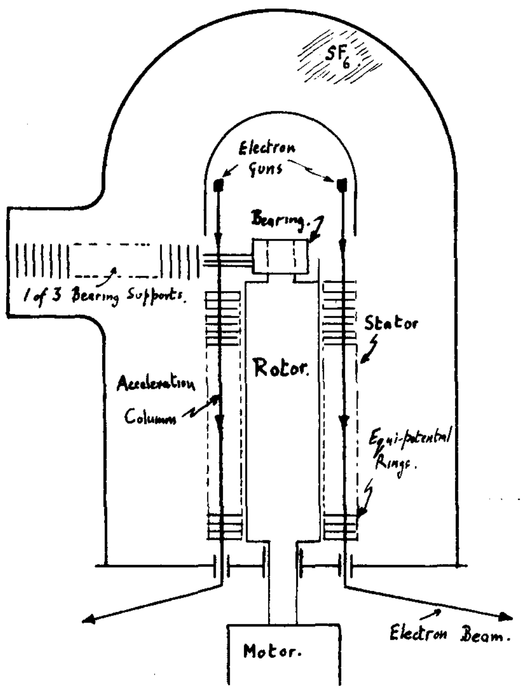


Figure 2. Schematic diagram of the High Voltage D.C. Generator.

After focusing the bunches enter an acceleration column where they gain their full energy. A high initial rate of gain of energy is essential to minimise space-charge divergence of the bunches. Focusing of the beam is continued in the column by means of quadrupoles, and the emerging beam, now relativistic, minimises space-charge blow-up by its self-focusing properties.

The acceleration column supports a D.C. voltage of several MV. In principle there are several ways of producing this voltage, depending upon the beam power required. At low beam powers an I.C.T. might be used, whereas some variant of the rotating shaft type of generator would probably be necessary at high power level. An elementary design for a large, high power generator to deliver 10 MW of power has been evolved on paper.

Supposing that the acceleration column can be designed so as not to exhibit any resonance phenomena at the periodicity of the electron bunches, then the efficiency of the acceleration process can be very high, literally approaching 100% if there is no loss of beam to the column.

## Beam Coupling to Cavities

Since the electrons are assumed relativistic there will be a negligible amount of de-bunching during transport of the beams to the interaction cavities. The particular point at which a beam passes through a cavity determines the energy and current requirements of the beam, so that there is considerable latitude in matching the D.C. generator to the main accelerator.

Naturally, the process of energy transfer from the electron bunches to the fields in the cavities is almost 100% efficient as there is no intermediate process involved, and other losses, such as synchrotron radiation, are completely negligible.

For reasons associated with the overall efficiency of operation of the machine it is desirable to couple the electron beam into the cavities at zero phase angle, that is, the electrons are decelerated over the crest of the waveform. Since the beam loading proper of the cavities is at the phase-stable angle $\phi_s$, the cavities will be reactively loaded in proportion to the magnitude of the beam loading. As in other machines, this effect can be accommodated by appropriate detuning of the cavities.

Following each deceleration the average value of $\beta$ for an electron bunch decreases and so the flight path to succeeding cavities must be reduced suitably at each crossing. Of the many ways in which this can be accomplished a particularly attractive method is to change the relative location in azimuth of the cavity walls in the neighbourhood of the flight path of the electron beam, and simultaneously guide the beam at slightly less than the synchronous radius. In this way the bunches pass through each cavity at the same radius from the machine centre and so the energy loss to each cavity is identical. Adjustment of the relative azimuthal locations of the cavity walls near the electron flight path is also a convenient way to control the relative phasing of the cavities.

## Stability of Operation

An interesting feature of this machine is the self-regulatory nature of the interaction of the electron beams with the cavities. The rate at which energy is transferred to the cavity fields is proportional to the product of the cavity voltage $V_c$ and the electron beam current $I_c$, whereas the rate of loss of energy to the cavity walls is proportional to the square of the cavity voltage. Thus the magnitude of the cavity voltage in steady-state conditions is directly proportional to the electron beam current. Additional losses caused by proper beam loading are proportional to the product of cavity voltage and accelerated beam current, $I_b$.

Under steady conditions this gives

$$V_c I_e = k_1 V_c^2 + k_2 V_c I_b \qquad (1)$$

If the electron current is made proportional to ($k_2$ $I_b$) plus an additional current $i_e$ then

$$I_e \equiv (k_2 I_b + i_e) = k_1 V_c + K_2 I_b \qquad (2)$$

and so

$$V_c = i_e/k_1 \qquad (3)$$

Provided the electron current is related to the accelerated current in this manner the system is entirely stable, any transient departures, such as caused by sparking, decaying rapidly with a characteristic time of $Q_L/\pi f$.

An additional feature is that if there is no loss of electron current during the process of deceleration then the magnitudes of the cavity voltages are automatically made equal.

Finite Transit Time Effects

The principal effect of a finite transit time on the electron beam is to introduce a dispersion in the energy of the bunches following deceleration. Such dispersion is of little consequence provided the particles remain relativistic in energy, but tends to dominate the behaviour of the bunches during the final stages of deceleration.

Since loss of electron beam in the last cavity should be avoided if the cavity voltage amplitudes are to be maintained constant, then a minimum requirement is that all electrons in a bunch should leave the last cavity with finite energy. If there is an appreciate energy dispersion then the overall efficiency of the system is reduced, as the energy of the emergent beam from the last cavity is lost to the system. Added disadvantages of dispersion are a progressive increase in emittance of the electron beam and a tendency to debunch.

To minimise such dispersion the electron beam is coupled to the cavities at zero phase angle. The residual dispersion for a beam of reasonable phase-spread is still unacceptably large, and so the beam is arranged to pass through a small cavity resonator following each deceleration. These correction cavities are operated at a high harmonic of the main cavity frequency, and simply reduce the dispersions in energy to an acceptable amount. The high frequency and low amplitude of signal needed in these correction cavities leads to quite modest power requirements for their excitation. Further, most of the energy given to the electron beam in these cavities is usefully coupled into the acceleration cavities. In this manner the average energy of the beam emerging from the last cavity can be as low as 0.2 MeV, and with a phase spread of $70^{\circ}$.

Since the electron beam traverses the main cavities at zero phase the magnetic component of the electro-magnetic fields in the cavities produces a minimum effect on the beam. Excepting in the special case where the electron beam crosses the cavity in the region where the magnetic component is essentially zero on the median plane, some increase in beam emittance will be produced. One way to minimise this effect is to introduce small correction fields, perhaps using the magnetic component of the fields in the waveform-correction cavities described previously.

Overall Efficiency

There are two major losses of efficiency in the proposed machine complex: in the ohmic, frictional and viscous losses associated with the high voltage generator, and in the residual energy of the beam emerging from the last deceleration cavity. It is conceivable that these losses could be sufficiently reduced so as to permit an overall efficiency of operation in excess of 90%.

Although the Super-SOC idea bears some resemblance to a klystron in its mode of operation, the efficiency is not restricted to the well-known '58%' limit[4] associated with conventional klystrons, nor even the modified '74%' limit. One reason for this difference lies in the method of bunching.

Start-up Procedure

Two stages are necessary to initiate operation of the machine; first, the cavities are excited up to their correct working voltages and, secondly, the main beam is then introduced in a controlled manner. During the initial excitation of the cavities two alternative procedures can be followed to accommodate the changing nature of the electron beam, but in both cases the electron beam is assumed to be introduced to the machine at full energy although at a reduced intensity. One method is to simply initiate the electron beam and wait for a time of Q.N seconds, where N is the number of cavities excited by an electron beam. Typically, this interval is about one millisecond per cavity. As each cavity reaches operating voltage the emerging electron beam then is suitable for excitation of the next cavity. Water cooling of the electron beam flight tube in the high energy region might be necessary in this method to absorb the transiently split beam (typically $< 2$ Kw. sec.total).

An alternative method is to incorporate small pulsed bending magnets along the flight path so that the electron beam, which initially will be too energetic for all but the first cavity, can be suitably guided through the cavities during the process of build-up of the voltages.

In both cases the phases of the cavities are automatically correct once the full voltage conditions have been reached, although in the second method some slight changing of

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phase occurs during the build-up process.

## Low Energy Modification

In stages of low primary beam energy the design of the machine would be complicated unnecessarily by operating with the secondary electron beam at the $R_\infty$ radius. Instead, the electron beam can be designed to circulate at half this radius, provided the mode of operation of the machine is adjusted suitably. The cavities are then spaced in azimuth at intervals of $2\beta\lambda$ so that particles are accelerated once every two cycles of the radio frequency. Stages operating in this manner can be joined to others operating at $R_\infty$ without change in the frequency of operation or bunching ratio, that is, the area in longitudinal phase-space remains constant.

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