A RECIRCULATING LINAC AS AN INJECTOR FOR SMALL STORAGE RINGS OR FREE ELECTRON LASERS

W.A. Gillespie
Dundee College of Technology, Dundee, Scotland
E.A. Hughes and N. Marks
SERC Daresbury Laboratory, Warrington WA4 4AD, England
G. Saxon
Accelerator Physics Consultant, 32 Thorn Road, Stockport SK7 1HQ, England

Introduction

There is an increasing interest in the use of small storage rings to produce synchrotron radiation for such purposes as lithography. Clearly, such rings need injectors and the provision of these can add significantly to the overall cost of a storage ring project in terms of both hardware and space requirements. There is a need therefore to consider the most cost-effective way of providing for injection. It is suggested that the recirculating linac (or double-sided microtron) design proposed here meets this aim at least for injection energies up to about 450 MeV and maybe higher.

The concept on which the proposal is based was first given by Kaiser[1], who called it a bicyclotron. It modifies the race-track microtron by having two accelerators per orbit. This, of course, means having four 90° bending magnets instead of two 180° magnets. As Kaiser pointed out, this reduces the pole-face area by a factor of 2.8. The principal difficulty in his scheme lay in the fact that the pole ends presented a 45° angle to the beam orbit, causing almost insuperable difficulties in focusing, due to edge fields. In the present proposal this is overcome by having sufficient energy gain per orbit to allow the use of a stepped pole contour such that electrons can enter and leave the magnets at right angles to the pole face (or else at some small angle determined by the overall focusing). A large orbit separation also allows the insertion of quadrupoles in each separated orbit. Since the energy on each orbit is fixed, compact permanent magnet quadrupoles may be considered. A schematic view of the layout of a machine based on these ideas is shown in fig.1, this being a 100 MeV version, but higher energies are clearly obtainable. It is noted that this basic idea formed part of an early Argonne proposal for a double-sided microtron[2].

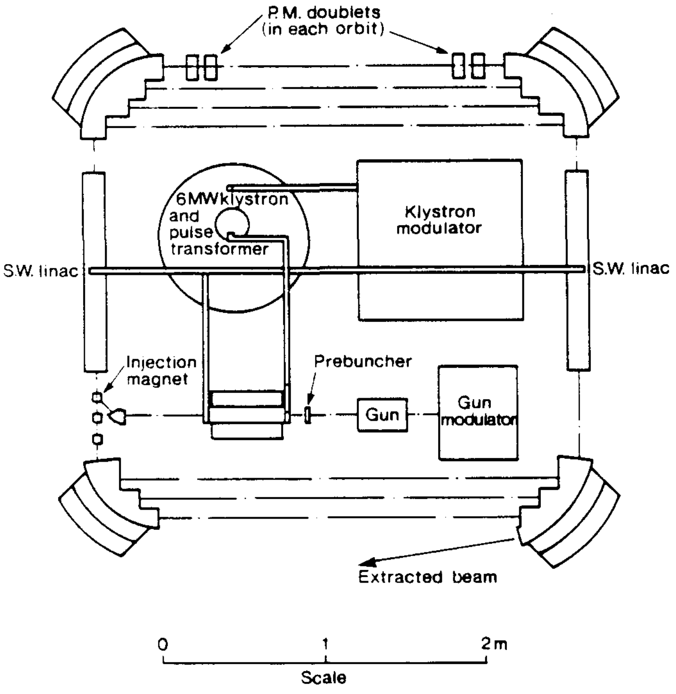

Fig.1. Tentative layout for a 100 MeV recirculating linac.

In order to obtain the high energy gain per pass, whilst keeping the system compact, standing wave linacs would be used, in conjunction with commercially available klystrons at output powers dependent on the final energy requirements. Such klystrons are, of course, basic to any type of injector and, together with the associated modulator and power supplies, form a major part of the cost of an injector. It is important therefore, that a klystron is used to maximum advantage.

An alternative use for this device, probably in the lower energy range, is as an injector for a free electron laser. The requirements for such an injector have been reviewed[3] and are considered in a later section of this paper.

Energy Gain and r.f. Power

Various structures for standing-wave (sw) linacs have been assessed both theoretically and experimentally at Los Alamos[4]. Three of these, currently in use, are the on-axis coupled structure (slot-coupled), the disk and washer structure and the side-coupled cavity arrangement. It was found that, whatever the theoretical predictions, there is little to choose between them with regard to shunt impedance as obtained in practice. A shunt impedance of 80 MΩ m^{-1} would appear to be readily achievable at S-band. The choice must depend on which is the easiest to make.

The achievable energy gain in a length, L, of linac is $V = \sqrt{ZT^2L\,P_c}$, where P_c is the power dissipated in the structure, and ZT^2 is the transit time corrected shunt impedance per unit length, which is taken to be 80 MΩ m^{-1}. Commercially available klystrons, at S-band, range in power output from 6 to 35 MW, whilst developments at SLAC are pushing peak powers even higher.

It is assumed that the present design will be more feasible if electrons are already relativistic, say 2 MeV, before injection. Accordingly, the klystron output must first provide power for the pre-injector before being fed to the main accelerators.

The power, P_{in}, supplied to a given linac section must provide for both copper losses and for beam loading. In the steady state $P_{in} = P_c + nVI$, where n is the number of orbits and I is the circulating beam current, V is the energy gain. Since $P_c = V^2/ZT^2L$,

$$V = \left[-\,nI + \sqrt{n^2I^2 + 4\,P_{in}/(ZT^2L)}\right]\,ZT^2L/2$$

Fig.2 shows the values of V for various values of P_{in}, the input power to a section, as a function of nI for two different lengths of structure.

The first electrons injected see the field due to the full stored energy and so achieve the no-load energy gain. With a cavity with a Q of the order of 15,000

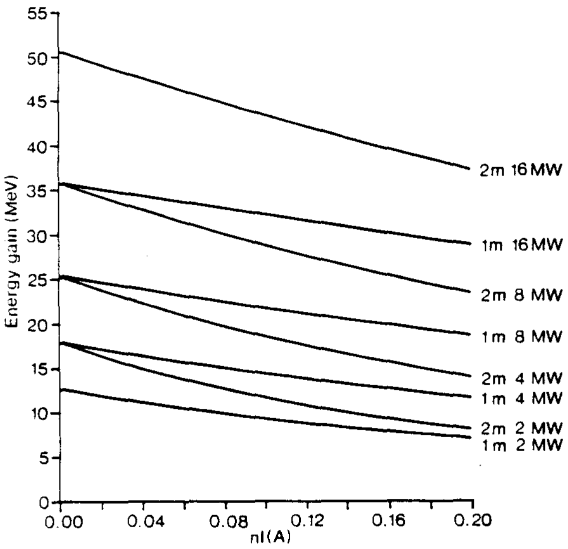

Fig.2. Energy gain vs. beam loading at various input powers for structure lengths of 1 and 2 m.

it will take a few microseconds to achieve a steady state or for the field to be altered by change of the drive power. But in this type of machine the energy gain must be constant under all conditions. One must, therefore, overcome transient beam loading effects.

Bending Magnets

The stepped bending magnets (fig.3) are unconventional in their pole geometry and this feature leads to novel problems in their design. These will be investigated using three-dimensional field calculations to ascertain the field distribution in the gap and in the fringe field regions. The latter will almost certainly affect the beam orbits unless compensating or limiting measures are taken, such as the use of shims and/or appropriate pole angles.

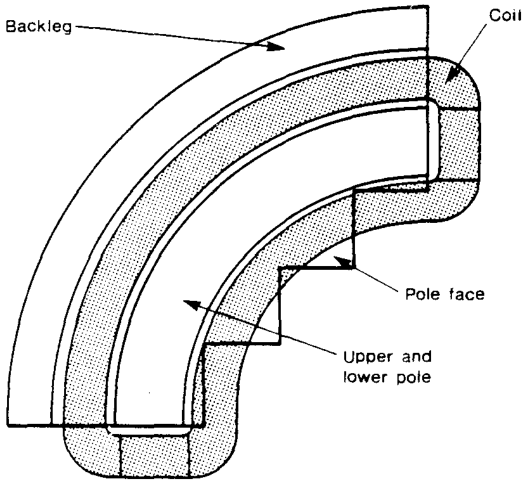

Fig.3. Plan view of stepped pole magnet.

The outline design of fig.3 may be suitable for gap fields up to 1 T. A different geometric arrangement might be necessary to achieve higher fields.

Focusing

The transverse control of the beam is based on the principle of making the bending arcs achromatic, using the two 90° magnets and two quadrupole doublets, these being as near as possible to the bending magnets. The principal problem lies with the first, small radius, bend. This arises because a radial offset at entry to a 90° magnet is converted to a divergence proportional to the inverse of the bending radius.

Figure 4 illustrates the scheme for a particular case in which the final energy is about 100 MeV. The parameters for this are given in table 1, whilst fig.5 shows the trajectory of an extreme electron between the first and second bending magnets. Also shown is the third orbit which is even more contained.

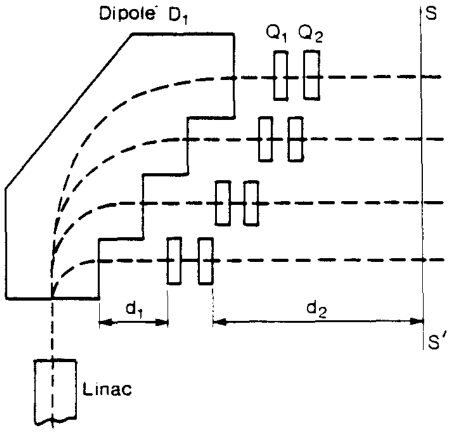

Fig.4. Arrangements of quadrupole doublets at the first bending magnet.

Table 1. Parameters for a typical machine.

Final energy	100 MeV
Injection energy	2 MeV
Energy gain/pass	12.5 MeV
Klystron power	6 MW
Power per linac	2 MW
Linac length	1.5 m
Current loading	14 × 4 mA
Magnetic flux	0.479 T
m	4

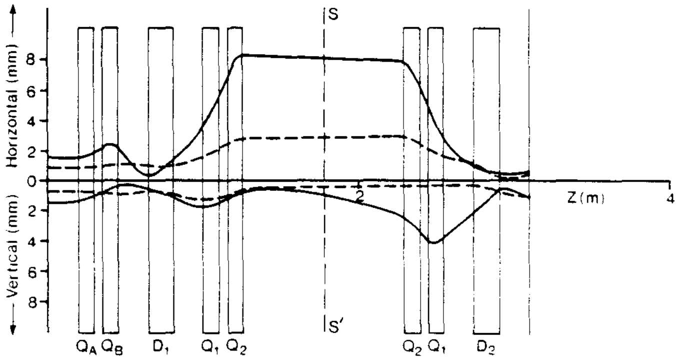

Fig.5. Extreme electron orbits between first and second linacs. Normalised emittance is 50 × 10^{-6} m rad. Energy spread at 2 MeV is ±5%.

An advantage can be obtained, on the first orbit, by introducing a doublet between the end of the first linac and the first bending magnet to reduce the radial width of the beam at entry to the magnet (see fig.5).

Phase Stability

The energy/phase relationship has been investigated for a range of design parameters and it is clear that there will be no problem, even with m=4. Phase space is contained at least over 8 orbits for stable phase angles ranging from 72°-80°. Figure 6 illustrates the phase/energy error for electrons injected at ±6° from a stable phase angle of 80°. It should be possible with a well designed pre-injector to ensure that the electrons lie well within this phase range and with energy errors less than ±0.2 MeV.

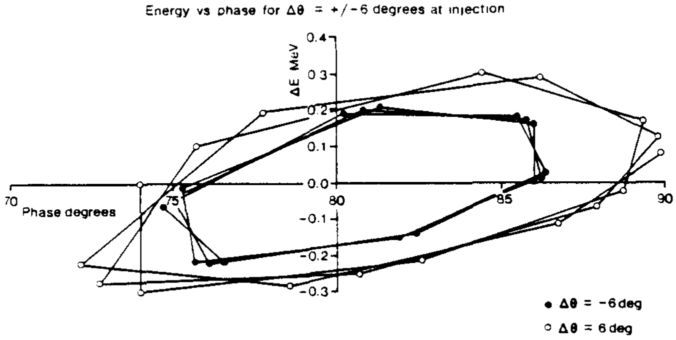

Fig.6. Phase/energy error plots for electrons injected ±6° from a stable phase angle of 80°. These plots are for 8 complete orbits.

Requirements for a Storage Ring Injector

So far only the basic principles of the scheme have been outlined. For a storage ring injector there will be an emphasis on the maximum energy achievable using a single klystron. Although full energy injection makes storage ring operation easier, it is an unnecessary luxury. There are successful storage rings with injection at much less than the final energy.

With a 35 MW klystron and using 6 orbits the present system is probably satisfactory for energies up to 450 MeV. The 90° bending magnet is feasible up to at least 1 GeV. If the permissible injection rate determined by the storage ring damping time is 1 Hz then a current of 10-20 mA will ensure a satisfactory filling rate.

Requirements for an FEL Injector

The essential requirements for an FEL injector are low energy spread, low emittance, high peak current and, if oscillation is aimed at, a long macropulse length, ideally cw. It has been demonstrated that the final energy spread will be determined by the phase and energy spread at injection. With a carefully designed injector the phase spread at 2 MeV could be kept to ±3° and the energy spread to ±0.1 MeV. This leads to an output energy spread of within ±0.2% at 100 MeV, which is acceptable in most cases.

Emittance considerations have been discussed in a number of papers[3,5,6]. This is determined by the whole process of injection from the gun to the 2 MeV linac. It will not be made any greater in the recirculating machine.

With regard to pulse length, this is important in ensuring oscillation to full saturation even at a low gain/pass. Certain manufacturers offer long pulse klystrons, e.g. 100 µs, at sufficient peak powers to be of interest. High peak currents arise from sub-harmonic bunching of the electrons. By this means, peak currents of the order of tens of amperes can be achieved even though the circulating current in the machine is only, say, 20 mA. At Boeing[7] a peak current of over 100 A has been achieved with a normalised emittance of 80×10^{-6} m rad (0.008 cm rad).

Conclusions

A clearly defined technology has been demonstrated for the achievement of moderate energies suitable for either injection into storage rings with an operating energy of 0.5-1.5 GeV or for injection into FEL devices. The approach outlined is considered to be the most cost-effective way of injection, as well as allowing the possibility of other desirable technical properties.

The maximum energy obtainable with this device is probably about 450 MeV, unless one uses superconducting r.f. This is what can be achieved with a 6-turn orbit and a single high-power klystron. The whole arrangement is compact in terms of space requirements which gives a further overall cost saving, e.g. for shielding. The desired properties of the electron beam will be mainly determined by the injector design.

References

1. K-H. Kaiser, "A Possible Magnet Configuration for a Recycling Accelerator in the GeV Range", presented at the Conference on Future Possibilities for Electron Accelerators, Charlottesville, VA, Jan. 8-10, 1979.
2. Y. Cho et al., "Design Study for a 2 GeV double-sided microtron", presented at the 11th Int. Conf. on High Energy Accelerators, Geneva, July 7-11, 1980, p.115.
3. G. Saxon, "State of the art of low energy accelerators for FEL operation", presented at the Conference on Free Electron Lasers, Castelgandolfo, Italy, Sept. 3-7, 1984.
4. R.K. Cooper et al., "Radio frequency structure development for the Los Alamos/NBS Racetrack Microtron", Los Alamos Report 83-95 (1983).
5. D.C. Quimby and J.M. Slater, "Electron beam quality requirements for a tapered wiggler free electron laser", J. Quantum Electron. Vol. QE21, pp. 988, (1985).
6. C.W. Roberson, "Free electron laser beam quality", J. Quantum Electron. Vol. QE21, pp. 860, (1985).
7. J.M. Adamski et al., "The Boeing double sub-harmonic electron injector-performance measurements", Trans. IEEE, Vol. NS-32, pp. 2994 (1985).