Study of a 10 MeV, 50 kW Racetrack Microtron for Industrial Radiation Processing

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Abstract

The possibility of using a racetrack microtron equipped with an L-band linac for irradiation processing has been studied. Extraction of both 5 and 10 MeV electron beams is possible and the beam power was calculated to be at least 50 kW at 10 MeV. A beam split extraction and an achromatic transport system for double-sided irradiation at 10 MeV is also discussed.

1. INTRODUCTION

Interest in high current accelerators in the energy range of 5 to 10 MeV for use in industrial irradiation applications has grown in recent years. The beam power at 10 MeV electron energy is normally 20 to 50 kW. At 5 MeV the power requirements are generally much larger as electrons at this energy often are used for bremsstrahlung generation with low (~5%) electrons to photons conversion efficiency. A linear accelerator (linac) is most commonly used at 10 MeV, while at 5 MeV the accelerator of preference so far is high power DC-type.

The racetrack microtron (RTM) equipped with a small standing wave linac offers a competitive alternative to the linac in size, beam quality, stability, power conversion efficiency and cost.

2. THE RACETRACK MICROTRON

The principles of acceleration in a racetrack microtron explained elsewhere[1], are briefly outlined here. In a RTM a linear accelerator is inserted between two bending magnets. The recirculating electrons are already relativistic in the first orbit, giving a linear increase in revolution time for each new turn, as the energy gain per turn is constant.

The resonant energy gain per turn is:

$$\Delta W = (W_0 + eV_{inj}) \frac{\nu}{\mu - \nu - \frac{2l}{\lambda}} \qquad (1)$$

where:

W_0	electron rest energy
eV_{inj}	injection energy
μ	number of RF periods to pass the first orbit
ν	time increase per orbit in no of RF periods
λ	wave length
l	distance between magnets

3. DESIGN CONSIDERATIONS

Table 1 lists the RTM parameters. ΔW was chosen to 2.5 MeV giving the possibility to extract both 5 and 10 MeV electrons from the accelerator. Generally 10 MeV is the upper limit for irradiation with electrons and 5 MeV is the maximum allowed electron energy for generating photons in industrial applications[2].

Table 1. 10 MeV RTM , General Parameters

Number of orbits	4
Energy gain per orbit	2.5 MeV
Pulse current	300 mA
Average output power	50 kW
Magnet field strength	0.22 T
RF input power	4 MW pulsed
Total length	1.2 m
Linac:	
Number of cavities	2 2/2
Frequency	1.3 GHz
Electrical length	345 mm
Power Loss at 2.5 MeV	0.7 MW pulsed

To handle a high power beam, a large aperture linac working at 1.3 GHz was found to be the best alternative. Using a linac with two half-wave and a quarter-wave cavity at each end gives a good compromise between compactness and low field strength, i.e. low power loss density in the copper structure. At an energy gain of 2.5 MeV the RF power loss due to the copper resistivity was calculated to be ~0.7 MW in pulsed power. The pulsed power was calculated by scaling the measured shunt impedance from a similar S-band linac. At 3 MW pulsed output power the input power requirements would be ~ 4 MW.

For $\mu = 7$ and $\nu = 1$ reasonable length and injection energy were obtained for the accelerator.

4. CALCULATIONS

All calculations were done for 10 MeV final energy. The program RCTRAK[3] tracks electrons injected with different energies, phases, divergences and off-axis coordinates. Evaluations of acceptance, energy spread, stability and alignment tolerances were done.

Magnet fields for the main bending magnets were calculated with the CERN-POISSON program and used as input in the RCTRAK simulations. Auxiliary poles with inverted magnetic field were used along the fronts of the bending magnets in order to ensure axial stability[4].

The phase acceptance is plotted in fig.1. The acceptance of ~37 % is quite good for an accelerator without any prebunching system. The injection energy was 30 kV, and the gun needs to deliver 0.83 A to obtain 300 mA pulsed output current. All electrons were found to be within an energy envelope of 6%.

Tolerances for both angular and longitudinal alignment of the bending magnets and for angular alignment of the linac were calculated. It was concluded that a normal overall alignment tolerance at the manufacture of 1 mrad angular and ±0.2 mm longitudinal is quite sufficient.

Variations in the bending magnet field of ±0.5 % do not change the acceptance significantly. A power supply with a 0.1 % stability would therefore be quite sufficient.

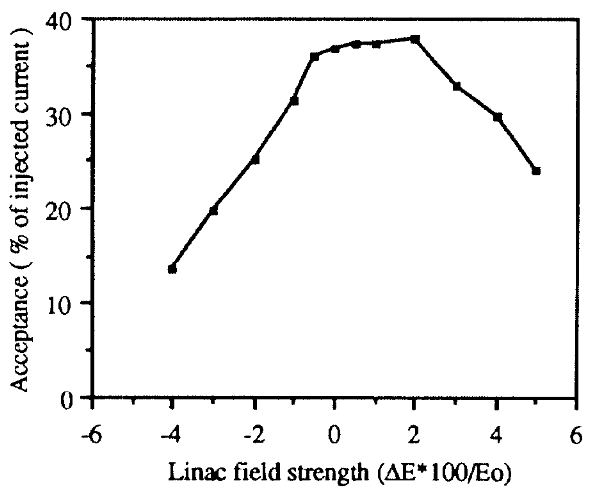

Fig. 1 Acceptance of the RTM at 10 MeV

RF stability constraints can be estimated from the phase acceptance plot in fig.1. The accelerator field strength can vary 2% without any large change in acceptance. As the field strength varies with the square root of the input power for an unloaded linac the overall variations in RF power (ripple + droop + pulse to pulse variations) should not exceed ±2% for stable operation.

As expected for a RTM with only four orbits and equipped with a large aperture linac there are only modest alignment or drift problems. The main problems are rather how to make a compact accelerator capable of handling large beam powers.

5. POWER HANDLING CAPABILITIES

The maximum output power is restricted by the power losses in the accelerator and how the accelerator handles this power dissipation. There are two main contributions to the dissipation, electrons lost in the accelerator and ohmic RF losses in the linac.

The calculations showed that almost all electrons that are lost outside the linac are lost in the first orbit. The lost electrons have such a low energy that they get too small a bending radius and actually is scraped off on the outside of the linac. Loosing 8% of the current under acceleration at 2.5 MeV gives 1 kW (2% of the 50 kW output power) deposited on the outside of the water cooled linac. This should not cause any problems.

Inside the linac most of the injected electrons will be lost in the first pass. More than 500 mA pulse current is lost, but some of the power will be returned to the RF as the electrons lost will be out of phase and decelerated in the linac before hitting the inner wall. A 500 mA pulse current lost at 0.6 MeV energy would give a pulse power loss of 0.25 MW at 1.7 % duty factor.

Dissipation due to ohmic losses in the linac was calculated to be 0.7 MW.

The total pulse power dissipated in the linac would be less than 1 MW which equals 17 kW continuous loss at 1.7% duty factor.

A standing wave L-band linac structure with combined radial and axial water cooling would handle power losses of about 150 kW/m [5], which is equivalent to about 50 kW for a 345 mm long 2 2/2 cavity structure.

So the power loss handling capacity of 50 kW for the linac gives a safety factor of 3, a reasonably good margin. In the most optimistic case with an allowable dissipation of 50 kW in the linac and a beam loading of 75% (3 MW pulsed power, 300 mA, in the output beam and 4 MW pulsed input power) the RTM would be able to deliver 150 kW beam power.

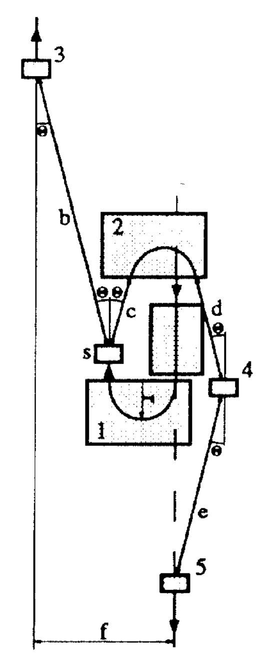

Fig. 2 Two way extraction

6. EXTRACTION

Two-sided irradiation is a desirable feature, since it obviates the need for product turn-over equipment. In many cases it is also the only solution to the problem of utilising beam powers of 50 kW and giving the right dose to products without overloading the product handling system.

The main problem of using two-sided irradiation with linacs is that the output beam normally has quite a large energy spread which makes it difficult to split and transport the high power beam through the various bending magnets along the beam line. With a well defined energy envelope of 6% the RTM may overcome this difficulty.

The proposed extraction scheme uses a beam split magnet, s, to extract two beams in opposite directions (fig.2). This provides for a simple design of the beam transport system for two-sided irradiation in fig. 3.

Using parallel edge magnets of the same size it is possible to have an achromatic extraction in both directions at 10 MeV. The machine will then be insensitive to energy variations within the defined 6% energy envelope.

With first order transport matrices[6], the solution for the achromatic case [7] is:

$$b \tan\theta = 2r \cos\theta - 2r_1 (1 - \cos\theta) \qquad (2)$$

for the left hand extraction and:

$$e = c + d - \frac{2r\,(1 - \cos\theta)}{\tan\theta} \qquad (3)$$

for the right hand extraction where r represents the RTM magnets bending radius and r_1 the extraction magnets bending radius, except for magnet 4 which has a bending radius of $r_1/2$.

Using achromatic bends with two 45 degree bending magnets and a quadrupole lens[5] in the remaining transport system as indicated in fig.3, would give an achromatic system all the way from the accelerator to either of the scanning magnets.

7. FEATURES

The recirculation in the RTM has several advantages. The "re-use" of the linac decreases the overall accelerating length. The resistive power losses in the linac copper structure is thereby reduced compared to a full length linac with the same accelerating gradient and shunt impedance per length. As a result the manufacturing cost of the linac can be kept low and the power conversion efficiency of the machine will be high.

There are also other advantages offered by the operating principles of the racetrack microtron:

- different energies can easily be obtained by extracting at different orbits.
- the bending magnets of the accelerator give good energy definition, eliminating the need for an external analysing bending magnet.
- the small energy spread and the possibility of extracting, at least at 10 MeV, electrons in opposite directions, provides for a simple design solution for two-sided irradiation.

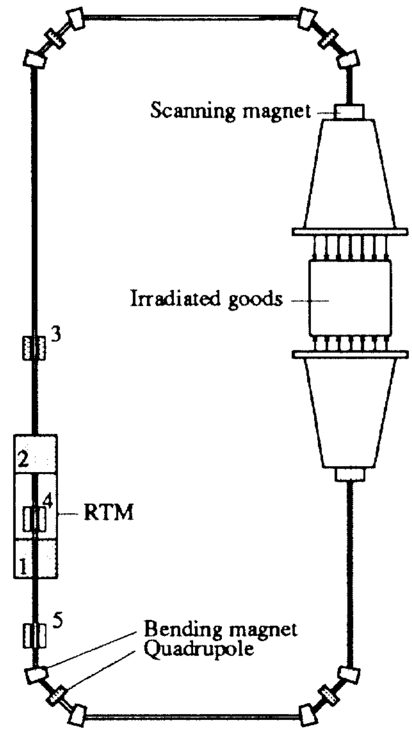

Fig. 3 Transport system for two-sided irradiation

8. ACKNOWLEDGEMENTS

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