Numerical and Experimental Results on the Beam Dynamics in the Rhodotron Accelerator

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Abstract

The 'RHODOS' paraxial particle code, including first-order transverse space charge effects, gives a rather complete picture of the beam dynamics in the CW recirculating Rhodotron accelerator. The calculations demonstrate the efficient focusing properties of the accelerator and the relatively weak sensitivity of its performance to the adjustment of the magnetic deflectors or the input RF power. These numerical results are in good agreement with the experimental measurements performed on the 3.3 MeV prototype.

1. Introduction

The Rhodotron is a new type of recirculating RF accelerator [1]. It uses a coaxial resonant cavity in which the beam is injected several times owing to magnetic deflectors placed around the cavity in its median plane (Fig. 1). This new concept leads to a compact and economical electron accelerator, particularly suitable for industrial applications which need a powerful beam (30-200 kW) in the 1-20 MeV energy range [2].

The prototype built at CEA Saclay, with a nominal energy of 3.3 MeV in 6 passes, has shown the feasibility of such a machine [3]. The tests have been performed in pulsed mode, because of the high beam losses in the first turns due to continuous beam injection. A new electron gun chopped at the 180 MHz cavity frequency is under development, with the aim of soon obtaining a continuous beam of 20 kW.

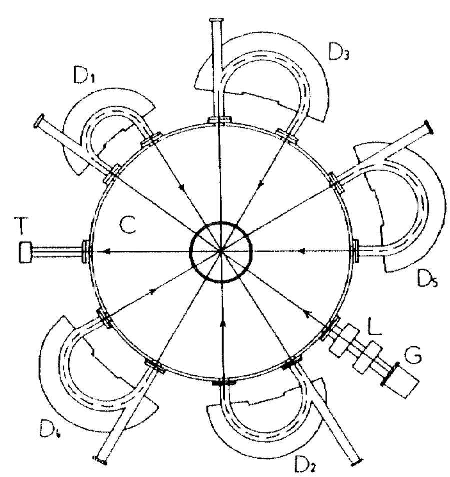

Figure 1. Median section of the Rhodotron prototype. G: electron gun; L: magnetic lenses; C: coaxial cavity; D: magnetic deflectors; T: stopping target.

For such beam currents, space charge effects are very important, at least during the first pass where electron energy is still low. The RHODOS code has been developed in order to understand these effects and to give an estimate of the beam losses in the walls and the deflectors for various injection conditions and accelerator parameters. This has been used to optimize the performance of the prototype, and also to design a 10 MeV, 100 kW machine suitable for industrial development.

In the following section we briefly describe the 3.3 MeV prototype, and in Section 3 we give the main characteristics of the modelization code. Numerical results will be given in Section 4 and compared with experimental measurements.

2. Description of the Prototype

Since a more detailed presentation of the Rhodotron prototype has already been done elsewhere [3], we just give here its main characteristics. Figure 1 shows a section of the accelerator in the median plane of the coaxial cavity, where the RF electric field is radial and maximum and the magnetic field is zero (fundamental TEM_1 mode). The magnetic deflectors have been represented, with their open-'V' shapped faces which perform vertical focusing through the fringing field while horizontal focusing is simply due to the deflection angle (> 180°). This is the only focusing device present in the Rhodotron (RF fields are alternatively focusing and defocusing), and simulations as well as experiments have demonstrated that it is sufficient for the purposes considered so far.

The operating parameters of the prototype are collected in Table 1. A peak current of 4 mA has been obtained at the nominal energy with a duty cycle of 1/1000, limited by the high beam losses due to the continuous injection.

Number of passes	6
Ouput electron energy	3.3 MeV
Cavity outer diameter	0.90 m
Inner-conductor diam.	0.225 m
Cavity height	0.92 m
Cavity frequency	180 MHz
Shunt impedance	12 MΩ
RF power (unloaded)	45 kW

Table 1. Characteristics of the prototype.

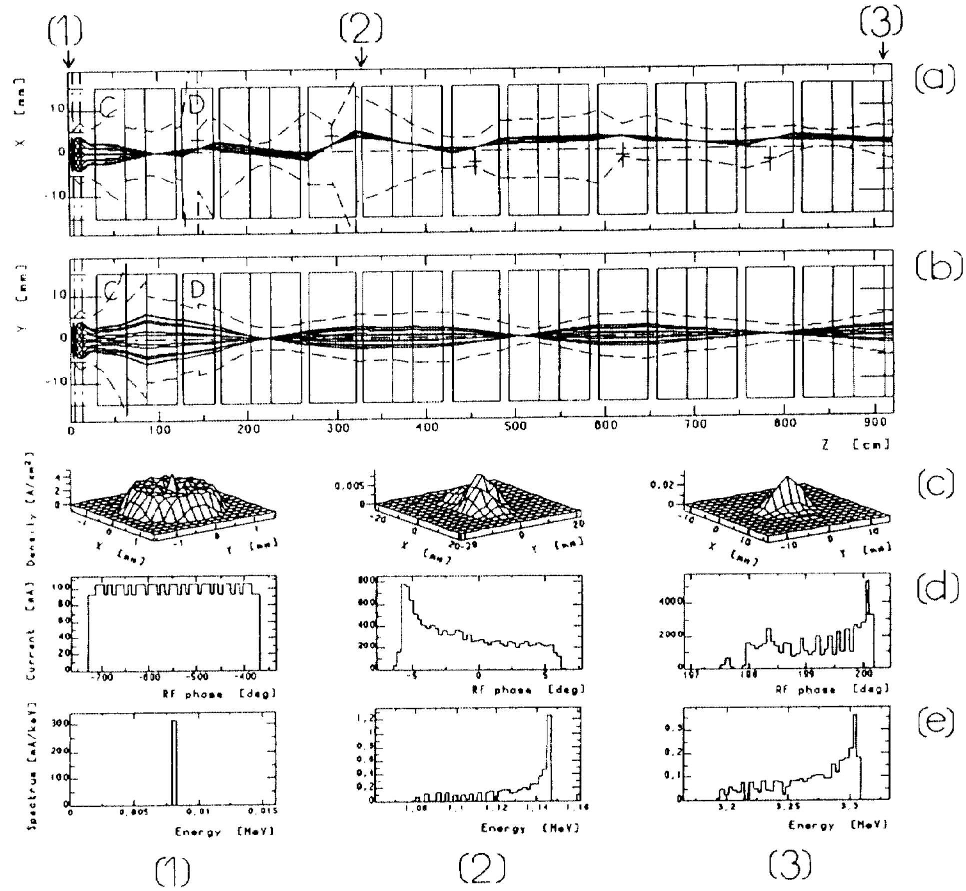

Figure 2. Simulation of the prototype configuration: trajectories in the (a) horizontal and (b) vertical planes (----: r.m.s. beam envelop; C: cavity; D: deflector; box heigh is equal to crossing-hole diameter); (c) areal density of current; (d) current pulse *vs* time; (e) energy spectrum. The plotted spots are taken (1) at the end of the gun, (2) at the entrance for the third pass, (3) at the exit from the sixth pass. Injection conditions: 8 keV, 100 mA continuous, 50 mm.mrad.

3. Main features of the modelization code

The RHODOS particle code integrates the motion equations for several thousands of macro-particles which are initially distributed on a square pattern in equally and uniformly charged, elliptical beam sections. Initial current pulses of any shape can be considered and initial emittance can be adjusted by randomly distributing the initial transverse speeds in the r.m.s. ellipse. Injector magnetic field, RF fields and particle motion are calculated in the paraxial approximation, including the local disturbance due to the crossing-holes. Transverse space charge fields are taken into account to the first order up to the end of the first pass, by considering at each section of the beam a monoenergetic, uniformly charged, elliptical cylinder. This is fairly exact as long as the energy transverse dispersion is low and each section is not too different from a uniform ellipse (typically all along the first pass), provided that longitudinal gradients in the beam are weak enough. No assumption is made about longitudinal distributions since the accelerator is intended to deal with long electron bunches due to large injection windows. Magnetic deflectors are described by first-order matrices, including fringing-field effects.

The code performs statistical calculations all along the beam path, and pictures of r.m.s. beam envelop, emittances, current pulse shape, energy spectrum, areal current density *etc*... may be obtained at different points of the path.

4. Numerical and experimental results

There is some difficulty in comparing the simulations calculated by RHODOS with experiments because some results require precise information about the electron source (spot size, focusing, extracted current...) that was not always available at the time of experiment. In particular, the estimate of final current by RHODOS is about twice higher than what has been measured in the continuously injected prototype. Bad knowledge of beam initial conditions and some geometrical defects observed in the deflector tubes should account for a large part of this discrepancy, more probably than higher-order effects. This will be studied in more details with the new chopped electron source.

Nevertheless, calculated spot sizes are globally in good agreement with the experiments, and the weak sensitivity of the relative output current to deflector adjustments is remarkably well described by the simulations.

4.1 Trajectories and spot pictures

Figure 2 shows the calculated beam along the path of acceleration, for a continuous injection at 8 keV with a 50 mm.mrad r.m.s. emittance. Interception of the beam by crossing-holes in the first pass (space charge effect) and by deflector tubes in the first two turns (spectrometer effect) is clearly indicated by the beam envelop aspect. Pictures of spots, current pulses and energy spectra show the beam evolving. The calculated, final current (actually from the third pass) is 11 mA, while the final (unnormalized) horizontal emittance is less than 10 mm.mrad.

4.2 Sensitivity to parameter adjustments

By performing complete simulations for various parameter values, it is possible to study the influence of parameter adjustments on the accelerator performance. As an example, Figure 3 gives the calculated curve of relative output current *vs* position of the first deflection magnet for the prototype configuration. Except for the absolute magnitude of current, this is in very good agreement with the experimental measurements made on the prototype. Moreover, the adjustment window is remarkably wide, which is among the original and very interesting properties of the Rhodotron.

4.3 Design of a 10 MeV, 100 kW machine

The 3.3 MeV prototype has been conceived with the only aim of demonstrating the feasibility of the Rhodotron. It has been consequently designed as a relatively simple machine at moderate power.

In association with the I. B. A. Company, an industrial machine is now under development. The aimed performance is 10 MeV, 100 kW, and for RF power optimizing, choice has been made of a 10 passes machine at 110 MHz. In fact, for such parameters the physics of the accelerator seems to be simpler than for the prototype case. Space charge effects in particular can be overcome because of higher optimum injection energy, with more favourable injection phase window.

Figure 4 shows the simulated trajectories in the case of a 10 MeV, 10 passes machine. A 60°-wide (1.5 ns) parabolic pulse of 12 mA mean current is injected at 55 keV with an emittance of 50 mm.mrad. According to the first-order modelization, the beam is accelerated without losses during the 10 passes and the beam output power is about 120 kW. In this configuration, the final horizontal (unnormalized) emittance is 5 mm.mrad and the r.m.s. energy spread is about 100 keV. The sensitivity to parameters adjustments still remains relatively weak, and for instance the adjustment window of RF peak voltage in the cavity for a beam transport without losses is more than 5 %.

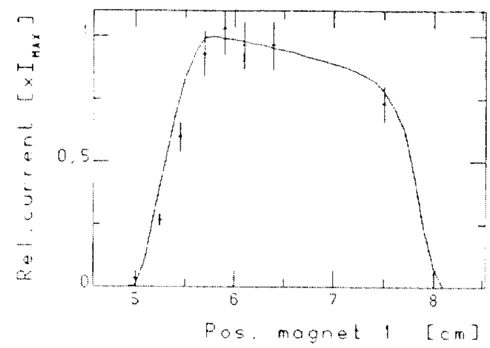

Figure 3. Relative ouput current *vs* position of the first deflection magnet in the prototype configuration (——: theoretical curve; + : experimental measurements).

5. Conlusion

We have reported the first numerical results obtained with the paraxial code RHODOS. This code has been developed in order to study the space charge effects in the Rhodotron, and more generally to estimate the beam losses on cavity walls and deflector tubes. Despite a discrepancy of a factor 2 between theoretical output current and measurements on the prototype, RHODOS gives a reliable description of the adjustment windows of accelerator parameters, such as magnet positions or intensities and RF field level. The weak sensitivity of accelerator performance to these adjustments is one of the very interesting properties of the Rhodotron.

Moreover, the code has been used to design a more powerful machine (10 MeV, 100 kW) now under industrial development in association with the I. B. A. Company. The relative simplicity and 'robustness' of the Rhodotron qualifies it as potentially suitable for industrial irradiation applications.

References

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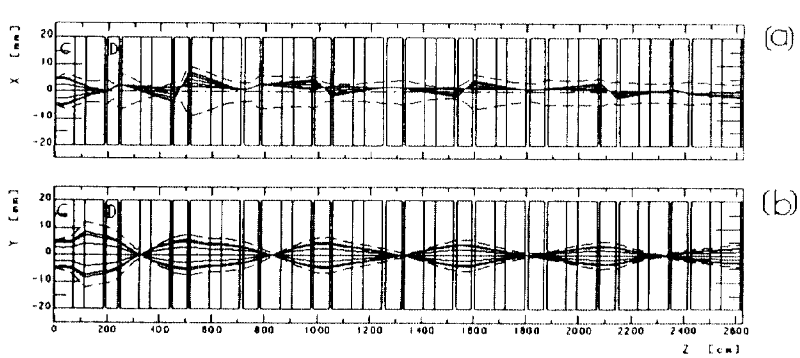

Figure 4. Simulation of a 10 MeV, 10 passes machine (see legend of Fig. 2). Injection conditions: 55 keV, 60°-wide, parabolic pulse of 12 mA mean current, 50 mm.mrad.