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A MICROTRON CYCLOTRON - THE "SLIPATRON"

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This paper investigates the design of microtron operating with an FFAG type of magnetic field. It has a constant frequency rf system with dees or cavities which have an extended radial width like those of a cyclotron. Its ion revolution period decreases each turn. This design will accelerate protons from 2 to 30 MeV. Its advantage over a cyclotron with the same magnetic fields at extraction is its lower magnet weight.

1 Introduction

All circular accelerators have an integral and usually constant number of rf cycles per turn. A microtron is unique in having a different number of rf cycles in each turn. The microtron, invented by Veksler, is described by many authors, for example by Jackson[1]. The classical microtron, used for relativistic electrons, uses an rf cavity in a uniform field magnet. It operates with an integral additional number of rf cycles in each turn. This system works for relativistic electrons because the path length in the magnet increases the same amount each turn if a constant energy gain per turn is used. Variations of the microtron using sector shaped magnets were suggested in the 1950's by Moroz[2], Zorin et al.[3] and Roberts[4]. The design of Roberts uses Thomas focusing, is designed for relativistic protons of several GeV and needs an injector like an FFAG machine at around 500 MeV. Doronin[5] proposed a lower energy microtron for protons of 1-500 MeV in which the period of a turn decreased with energy due to both its velocity increase and an adjustment of the path length of each turn. Muller[6] proposed a sector "Racetrack Cyclotron" for heavy ions at GSI. These designs used a narrow radial width single cavity or linac for acceleration.

The design described here uses a sector-focused type of field like that of a cyclotron, having a radial gradient like an FFAG machine, to accelerate protons in a microtron mode at constant rf frequency with a ion period that decreases with energy. A wide radial width cavity or dee system is used for acceleration. The velocity increases fast enough to make the orbit expand as it gains energy. It operates in the lower energy range of up to about 30 MeV/nucleon and is referred to in this paper as a "microtron cyclotron" or "slipatron". This paper investigates the possible parameters that can be used in the design. The advantages of such a design over that of a cyclotron with the same magnetic fields at extraction are that the magnet can be more compact, reducing its weight, and that there is more space for injection.

2 Design

The motivation for this design arises from the idea that a more compact magnet might be built, using sector cyclotron-type fields for focusing, by using an increasing radial gradient in the field and thus compacting the orbits. Deviating from the isochronous field causes the ion frequency to increase and the period to decrease with energy. To obtain high intensity we must use constant rf frequency and fill every rf bucket with beam, requiring an integral number of rf cycles between rf cavities, which is the microtron mode of acceleration. The harmonic number (rf freq/ion freq) then must decrease with energy gain. To allow a sufficient number of turns requires a high starting harmonic number of 50-100, so that it can be decreased during acceleration. A high energy gain per turn is required and can be accomplished with multiple dees. Unlike a microtron cavity, the dees have to extend over the radial aperture and to be synchronous with a range of ion periods. The range of periods can be covered by changing the angular width of the dee with radius, called "broad-banding" by Roberts[4]. Phase stability exists because the ion frequency depends upon radius. A table comparing some characteristics of constant field accelerators is shown is Table 1.

Table 1: Comparison of Accelerators

Parameters	Cyclotron	Microtron	FFAG	Slipatron
B(t)	Constant	Constant	Constant	Constant
B(r)	Constant	Constant	Increasing	Increasing
$f_{rf}(t)$	Constant/Variable	Constant	Variable	Constant
Harmonic	Constant	Variable	Constant	Variable
RF cavity radial width	Wide	0	Wide	Wide
Maximum energy	Low-High	High	Low-High	Low

The condition of requiring the radius to increase with energy can be understood in an approximate way by the simple relation:

$$2\pi R = V \times T \qquad (1)$$

where R is the radius of an orbit, V is its velocity and T is time of ion revolution. The change of these quantities in a turn is given by:

$$\Delta R/R = \Delta V/V + \Delta T/T \qquad (2)$$

To obtain an expanding orbit we must have $\Delta R/R > 0$. $\Delta V/V$ is positive and $\Delta T/T$ is negative, so we have the condition that the fractional increase in velocity per turn must be greater than the fractional decrease in period, to maintain a positive fractional increase in radius.

To explore the problem we need to try various combinations of parameters. There are many criteria to satisfy. We would like:

- A large compaction of the radial aperture required for the orbits, to reduce the magnet size and weight.
- A large acceleration between injection and extraction.
- An rf system with minimum power required.
- A high starting harmonic number to reduce the $\Delta V/V$, but not high enough to cause transit time problems at injection.
- A turn separation large enough for good injection and extraction.

To explore these problems it was found useful to use a spreadsheet, Microsoft EXCEL, for its easy calculation and tabular form. A number of designs were tried. Parameters for an optimized design are shown in Table 2. This design is for a proton accelerator with injection at 2 MeV and extraction at 30 MeV. The starting harmonic is 100 and the final value is 54. Average radius at extraction is .84 meter. The field gradient is obtained by tapering the hill gap, with constant hill angular width. The peak field on the hills at the edge is 19 kG. The axial focusing was calculated using the simple hard edge approximation with valley field assumed zero. The high flutter is adequate to compensate the negative n (field index) value and give Nuz of .3 or more using some spiral at the edge. The energy per turn is programmed from the center to the edge by dee shaping to give .2 MeV/turn at the center and 3.2 MeV/turn at the edge, a high value requiring multiple dees. The last column in Table 2 shows that a positive $\Delta R/R$ is maintained. The turn separation is 1.1 cm at injection and 1.7 cm at extraction. A figure of merit, F, for this type of accelerator is its radial aperture compared to that of a cyclotron. F = .7 for this optimized design.

A layout of this optimized design is shown in Figure 1. A four sector design is chosen to give two valleys for rf and space for injection and extraction. The magnet and rf systems are drawn to scale. Relativity was ignored since the mass increase is only 3%, compared to over 80% rise in field in this design. The rf frequency is 770 MHz. With 10 gaps in each of 2 valleys and 160 kV/gap at extraction the energy gain per turn is 3.2 MeV. The injection and extraction are shown schematically and no calculations were done.

A section of the rf system at the outer orbit is shown in Figure 2. An assembly consists of a stack of 10 of these 1/4 wave strip resonators. At the inner orbit the value of beta x lamda/2 is smaller, giving some transit time loss in energy gain, but only .2 MeV/turn is required there.

3 Conclusion

An accelerator configuration has been described which uses microtron mode rf operation and an FFAG type magnet. An optimized design was found for accelerating from 2 to 30 MeV. There may be better designs for this purpose and there may be heavy ion applications also, so further exploration would be interesting.

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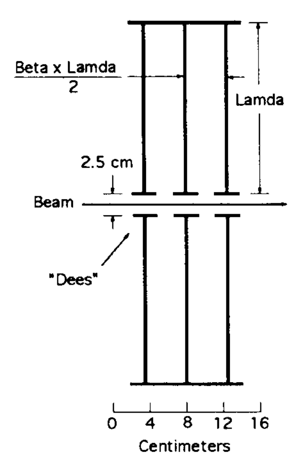

Figure 2: Section of dees at high energy
Vertical dimension not to scale.

Table 2: Parameter table for optimized design

Turn	E (MeV)	B-Rho (kG-m)	H	Bav (kG)	Rho-Av (m)	n	NuzSq	Eps (deg)	ΔE/E	Δv/v	Δt/t	Δr/r
	2-30 MeV, H1=100, ΔE/turn = Var. = .2 + .0062 x (Turn No. - 1)^2											
1	2.0	2.04	100	5.10	.399							
2	2.2	2.14	98	5.20	.410	-.74	.26	.0	.095	.048	-.020	.027
3	2.4	2.23	96	5.31	.420	-.85	.15	.0	.090	.045	-.021	.024
4	2.6	2.34	94	5.43	.430	-.89	.11	.0	.089	.045	-.021	.024
5	2.9	2.45	92	5.54	.441	-.86	.14	.0	.093	.046	-.022	.025
6	3.2	2.57	90	5.67	.453	-.80	.20	.0	.099	.049	-.022	.027
7	3.5	2.71	88	5.80	.467	-.74	.26	.0	.106	.053	-.022	.030
8	4.0	2.87	86	5.93	.483	-.69	.31	.0	.113	.056	-.023	.033
9	4.5	3.04	84	6.07	.501	-.65	.35	.0	.119	.060	-.024	.036
10	5.1	3.24	82	6.22	.521	-.62	.38	.0	.125	.063	-.024	.039
11	5.8	3.46	80	6.38	.542	-.61	.39	.0	.130	.065	-.025	.040
12	6.6	3.69	78	6.54	.565	-.62	.38	.0	.133	.066	-.025	.041
13	7.5	3.95	76	6.71	.589	-.63	.37	.0	.135	.067	-.026	.041
14	8.6	4.23	74	6.89	.614	-.65	.35	.0	.135	.068	-.027	.041
15	9.9	4.52	72	7.08	.639	-.68	.32	.0	.135	.067	-.027	.040
16	11.3	4.84	70	7.29	.664	-.73	.27	.0	.134	.067	-.028	.039
17	12.9	5.17	68	7.50	.689	-.78	.22	.0	.132	.066	-.029	.037
18	14.7	5.52	66	7.73	.714	-.85	.15	.0	.130	.065	-.030	.035
19	16.7	5.88	64	7.97	.738	-.94	.10	7.7	.127	.064	-.031	.033
20	18.9	6.25	62	8.23	.760	-1.04	.10	14.9	.124	.062	-.032	.030
21	21.3	6.65	60	8.50	.782	-1.17	.10	20.3	.121	.061	-.033	.028
22	24.0	7.05	58	8.79	.802	-1.34	.10	25.1	.118	.059	-.034	.025
23	26.9	7.47	56	9.11	.820	-1.55	.10	29.7	.115	.058	-.035	.023
24	30.1	7.90	54	9.44	.837	-1.84	.10	34.4	.112	.056	-.036	.020

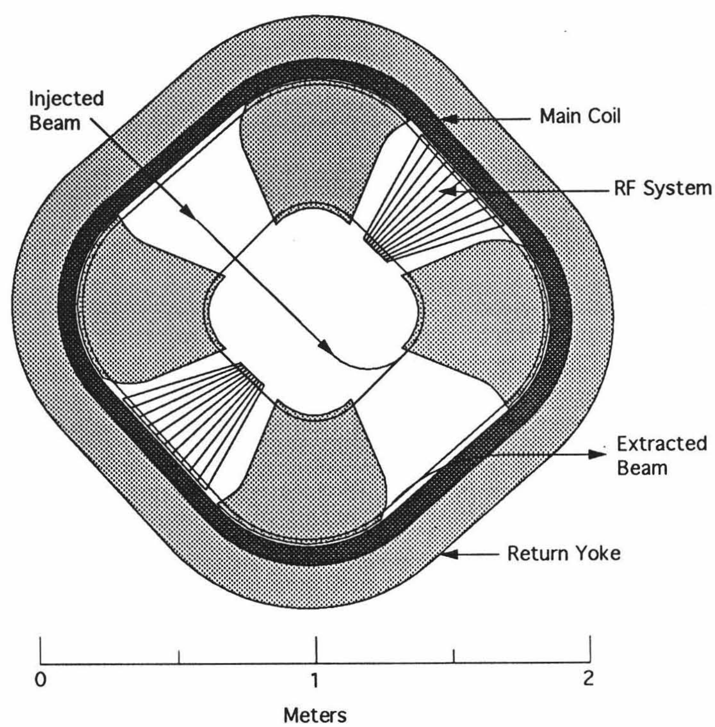

Figure 1: Optimized design layout