CYCLOTRON AND FFAG STUDIES USING CYCLOTRON CODES

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Abstract

This paper describes the use of cyclotron codes to study the beam dynamics of both high-energy isochronous cyclotrons using AG focusing and non-scaling (NS) FFAGs. The equilibrium orbit code CYCLOPS determines orbits, tunes and period at fixed energies, while the general orbit code GOBLIN tracks a representative bunch of particles through the acceleration process. The results for radial-sector cyclotrons show that the use of negative valley fields allows axial focusing to be maintained, and hence intense cw beams to be accelerated, to energies >5 GeV. The results for FFAGs confirm those obtained with lumped-element codes, and suggest that cyclotron codes will prove to be important tools for evaluating the measured fields of FFAG magnets.

INTRODUCTION

FFAGs are members of the fixed-magnetic-field or cyclotron family [1] and may be thought of simply as ring synchrocyclotrons with sectored magnets providing AG focusing. Nevertheless, cyclotrons and FFAGs have been developed by two different communities, which have sometimes taken different approaches in their work. The studies described here bridge this gap to some extent by applying orbit codes developed for isochronous cyclotrons to FFAGs, and some FFAG ideas to cyclotrons.

In recent years FFAG designs have generally been developed using synchrotron lattice codes – or adaptations of them – perhaps because their designers have mostly come from a synchrotron background. But synchrotron codes are poorly adapted for use in accelerators with fixed magnetic fields, where the central orbit is a spiral rather than a closed ring, and the magnetic field must be characterized over a wide radial range. Special arrangements must therefore be made to deal with momentum-dependent effects accurately.

Here, we report studies made with the cyclotron orbit code CYCLOPS [2], which tracks particles through magnetic fields specified on a polar grid and determines the equilibrium orbits (E.O.) at each energy and their optical properties. This has the advantages of:

- being designed for multi-sector machines with wide aperture magnets;
- allowing simultaneous computation of orbit properties at all energies;
- having the capability of tracking through measured magnetic fields.

In our initial studies [3, 4] we found good agreement with the orbit parameters determined by J.S. Berg [5] for his F0D0-2 10-20 GeV muon FFAG, and by Johnstone and Koscielniak [6] for their "tune-stabilized" FFAG for cancer therapy with 18-400 MeV/u carbon ions. (Both are of "linear non-scaling" or "LNS" design, where the magnets have constant field gradients.) But in the latter case, non-radial hard magnet edges proved tricky to model with a polar grid, even with a very fine mesh, leading to noisy results. To eliminate the noise, we smoothed the field's hard edges by introducing a sinusoidal field variation – an approximate but effective procedure. A variation extending over 4 grid spacings proved sufficient.

We report studies of three very different FFAG lattices and some cyclotrons. In one case CYCLOPS's sister code GOBLIN [7] has also been used to study accelerated orbits.

ISOCHRONOUS MUON FFAG

Rees [8] has proposed an isochronous radial-sector FFAG design (IFFAG) for accelerating muons from 8 to 20 GeV. This employs a novel five-magnet "pumplet" 0doFoDoFod0 lattice cell (from the Welsh word pump, pronounced pimp, for five), where the d magnets (and Fs at low energy) are reverse bending, and the d, F and D magnets each have special field profiles *B(r)*. With long drift spaces between the d magnets, and 123 cells, the circumference is 1255 m.

Méot *et* al. [9] have used the ray-tracing code ZGOUBI (originally developed for the study and tuning of mass spectrometers and beam lines.) to follow muons through a simulated field grid and confirm the orbit properties Rees predicts: good isochronism, and tunes that rise gently with energy, though ν_z exhibits some deviations (Figure 1). To achieve isochronism and vertical focusing at such high energies is not possible in regular FFAGs or isochronous cyclotrons with only two magnets per cell. By using more magnets, Rees gains additional free parameters.

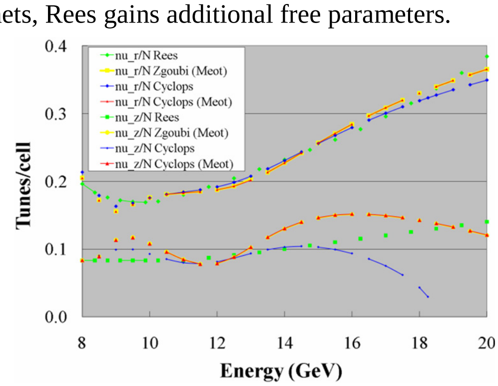

Figure 1: Betatron tunes in the isochronous IFFAG, as computed by Rees, Méot and CYCLOPS.

With CYCLOPS, sinusoidal edges were again needed to suppress noise. The tunes initially obtained [4] agreed

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moderately well with those published by Rees and Méot, though the values for ν_z diverged above 15 GeV. Subsequently we learnt that the latter's studies were made after some small adjustments in magnet position and field profile. With these adjustments included, the CYCLOPS results are almost identical to those of ZGOUBI (Figure 1).

REVERSE-BEND CYCLOTRONS

In the past, designs have been presented for isochronous ring cyclotrons to accelerate protons from 0.5 to 3.5 GeV and from 3.5 to 10 or 15 GeV [9-11], to provide cw, and therefore high-intensity, beams at these energies. The high spiral angles ε needed, however, lead to various practical problems: strong distorting forces on the magnet coils (particularly if these are superconducting), restricted space for rf cavities and injection and extraction equipment, and strong radial kicks during acceleration.

In view of these difficulties (and of Rees's intriguing results), it seemed interesting to explore how far the energies of radial-sector cyclotrons could be raised by using reverse-bend magnets to increase the flutter. This being an exploratory study, we made the simplest possible assumptions: N radial sectors, hard-edge magnets, no drift spaces, and equal but opposite hill and valley fields:

$$B_h = -B_v = \gamma B_0$$

To achieve optimum flutter, the field strength must of course be constant along the scalloped orbits – not along a circle. For maximum magnetic field B_m = 5 T, N = 15 sectors, and various values of the hill fraction h and "cyclotron radius" R_c, the tunes computed from a lumped-element model are shown in Figure 2 (in agreement with a CYCLOPS run for h = 0.60). The strong AG focusing pushes both ν_r and ν_z to the half-integer stopband $N/2$ = 7.5 at high energies – by 2.4 GeV for h = 0.6. This can be mitigated by increasing the width of the hills, h = 0.65 giving stable orbits up to 3 GeV with R_c = 6.5 m.

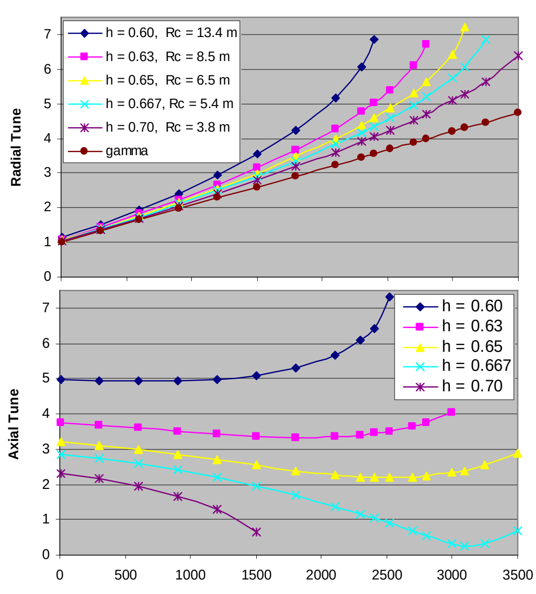

Figure 2: Tunes in a reverse-bend cyclotron with constant fields on orbit (N = 15, h and R_c as shown).

A more powerful way to reach higher energies is to increase the number of sectors. With N = 30 and the original h = 0.6 the ν_r = 15 resonance is raised above 5.5 GeV, with R_c = 14.9 m. The tunes computed by CYCLOPS are shown in Figure 3. Note the increasing deviation of ν_r and ν_z from the approximate formulae as the small-angle approximations for phase advance become increasingly invalid.

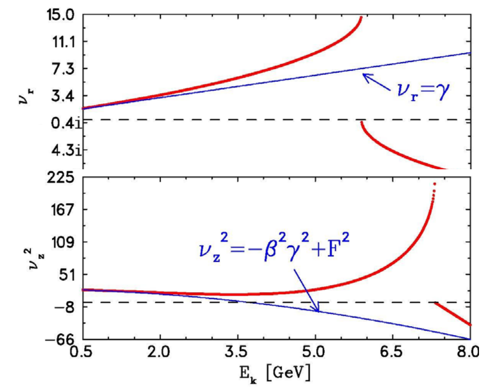

Figure 3: Tunes in a reverse-bend cyclotron with constant fields on orbit (N = 30, h = 0.6, R_c = 14.9 m).

PROTON FFAG FOR ADSR

C. Johnstone [11] has proposed a 2-stage proton FFAG, operating at fixed frequency, to drive a sub-critical reactor. We have studied the second (250-1000 MeV) stage, softening the hard-edge field minimally with an Enge function. The CYCLOPS results agree well with those from COSY, and are more extensive. (Figure 4).

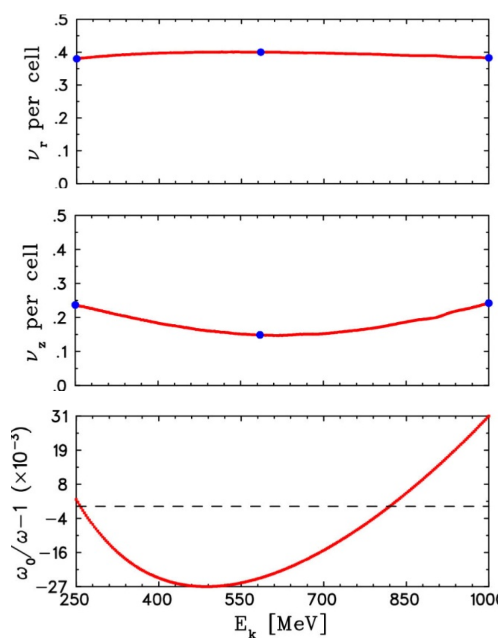

Figure 4: Betatron tunes and orbit time variation in the 250-1000 MeV FFAG for ADSR (•••• CYCLOPS, • COSY).

ELECTRON MODEL FFAG "EMMA"

EMMA [12] is a 10-20 MeV model of a 10-20 GeV muon LNS-FFAG for a neutrino factory, and is currently being commissioned at Daresbury. The lattice consists of 42 doublet cells, where the offset quadrupoles provide both bending and a linear field gradient.

CYCLOPS has been run both on the design "Baseline" hard-edge field [13], and on the measured combined field of the two quadrupole magnets. The results are shown in Figure 5 along with those of Giboudot [14] using other codes and Berg for the Baseline field. Agreement is good for the horizontal tune but less so for the vertical. In the case of flight time only relative values are plotted, so the vertical positions of the curves are of no significance. But there are real differences in the estimates for the energy of the minimum, for reasons unknown.

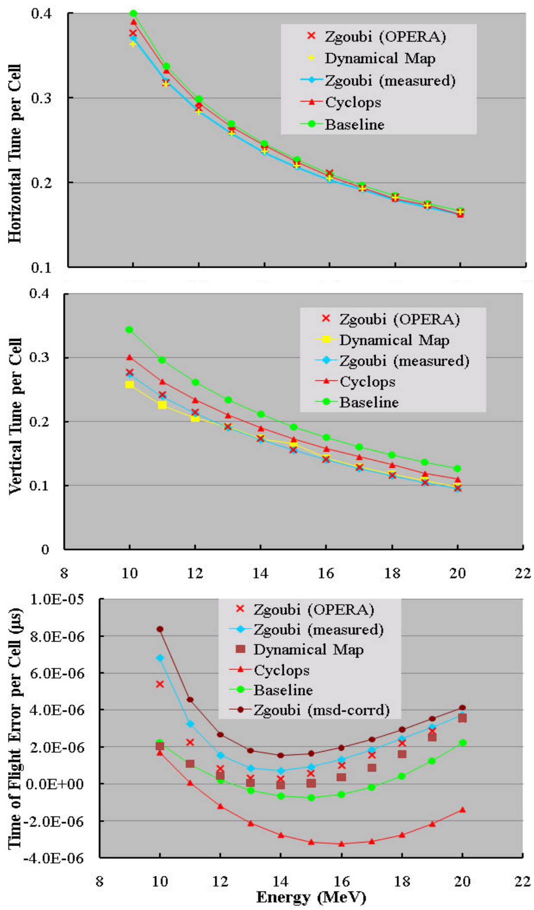

Figure 5: Tunes and time of flight error per cell in the measured EMMA field, as determined by various codes.

Accelerated Orbits

We have also run accelerated orbits in both the Baseline and measured fields using the GOBLIN code. A 4.3π eV-μs electron bunch was tracked over 5 turns through 21 evenly spaced 89-kV cavities. The initial phase was chosen midway between the two cusp trajectories (calculated by integrating the time-of-flight errors from CYCLOPS). Fig. 6 shows snapshots taken after passage through 0, 20, 41, 62, 83, 104 and 125 cavities. For the Baseline field the two upper plots show development of the bunch for radial emittances ε_x = 250π and 1400π μm, similar to that presented by Méot [15]. For the measured field (bottom plot) the bunch distortion is greater and the beam gains less energy.

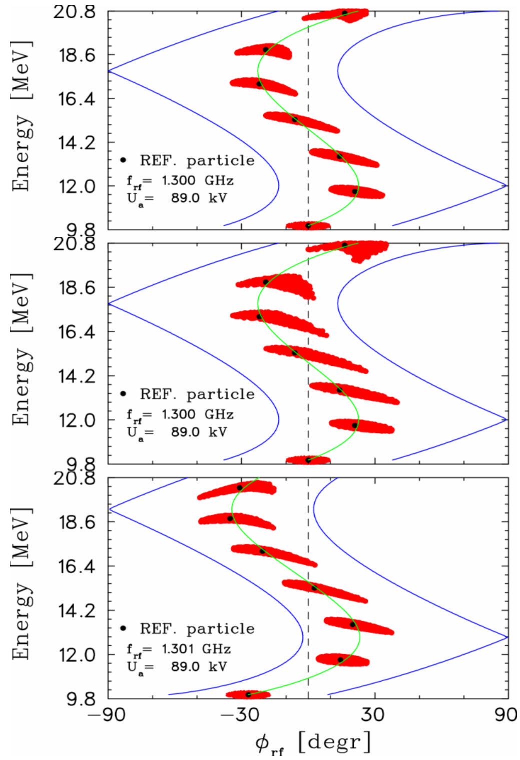

Figure 6: Energy-phase plots: (top) Baseline field, ε_x = 250π μm; (middle) Baseline field, ε_x = 1400π μm; (bottom) measured field, ε_x = 250π μm.

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