FFAG TRACKING WITH CYCLOTRON CODES

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Abstract

This paper describes tracking studies of non-scaling (NS) FFAGs using cyclotron codes in place of the more conventional lumped-element synchrotron codes. 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. Results are presented for the EMMA linear NS-FFAG under construction at Daresbury (10-20 MeV electrons), and for two non-linear NS-FFAG designs: Rees's isochronous IFFAG (8-20 GeV muons) and Johnstone's design for ADSR (250-1000 MeV protons). Our results are compared with those obtained using synchrotron and other tracking codes. In the case of EMMA, results are presented for both the measured and design fields.

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.

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, so that 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.

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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 smooth 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.

Here we report studies of three very different FFAG lattices. Besides CYCLOPS, in one case its 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.

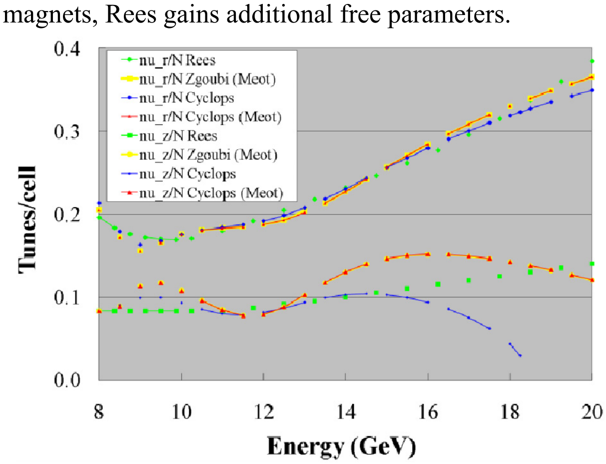

Figure 1: Betatron tunes in the isochronous IFFAG, as computed by Rees, Méot and CYCLOPS.

Because of its greater complexity, this lattice presented a greater challenge to producing an adequately detailed field map for CYCLOPS. With hard edges the tune values were sensitive to mesh size, and at some energies it was impossible to obtain orbit closure. But the use of sinusoidal edges was again effective. The tunes initially obtained with these [4] agreed 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).

PROTON FFAG FOR ADSR

C. Johnstone [11] has proposed a two-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 obtained using COSY (Figure 2).

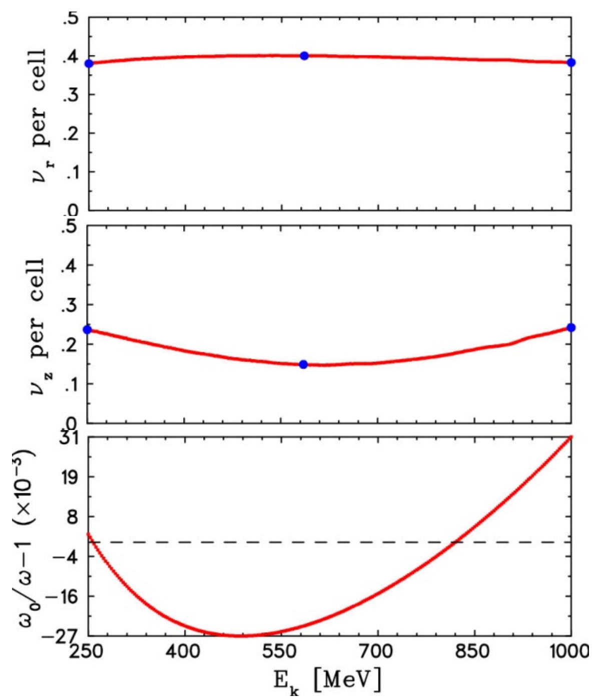

Figure 2: Betatron tunes and orbit time variation in the 250-1000 MeV FFAG for ADSR (▬ CYCLOPS, • COSY).

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 nearing completion at Daresbury. The lattice consists of 42 doublet cells, where the offset quadrupoles provide both bending and a linear field gradient.

Baseline (Design) Field

As EMMA is intended to demonstrate the feasibility of LNS operation (resonance crossing, serpentine acceleration), a broad range of tuning is built in to Berg's "Baseline" design [13], which assumes hard-edge magnetic fields. For CYCLOPS these were given minimal sinusoidal softening. The results are shown in Figure 3, along with those of other codes [14]. Agreement with ZGOUBI is excellent for all parameters. For ν_x and flight time CYCLOPS also agrees with Machida's S code, for ν_y with Berg's code.

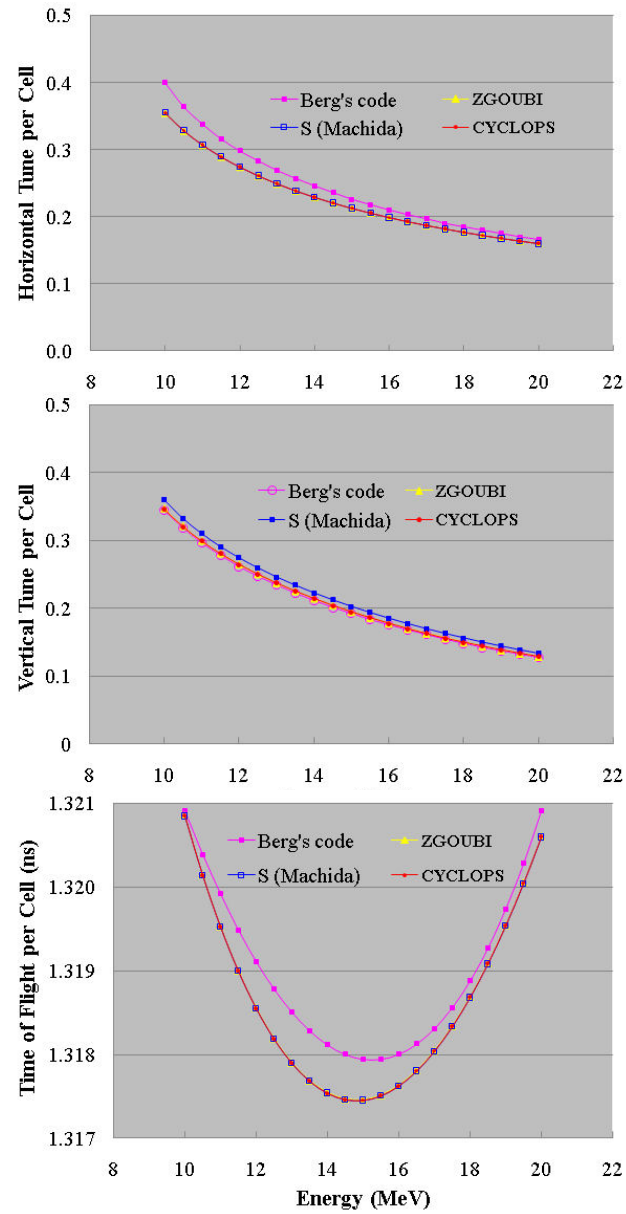

Figure3: Tunes and time of flight per cell in the EMMA Baseline field, as determined by various codes.

Measured Field

CYCLOPS has also been run on an early measurement of the combined field of the two quadrupole magnets. The results are shown in Fig. 4 along with those of Giboudot [15] using other codes and Berg for the Baseline field [13]. Agreement is good for the horizontal tune but poor 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.

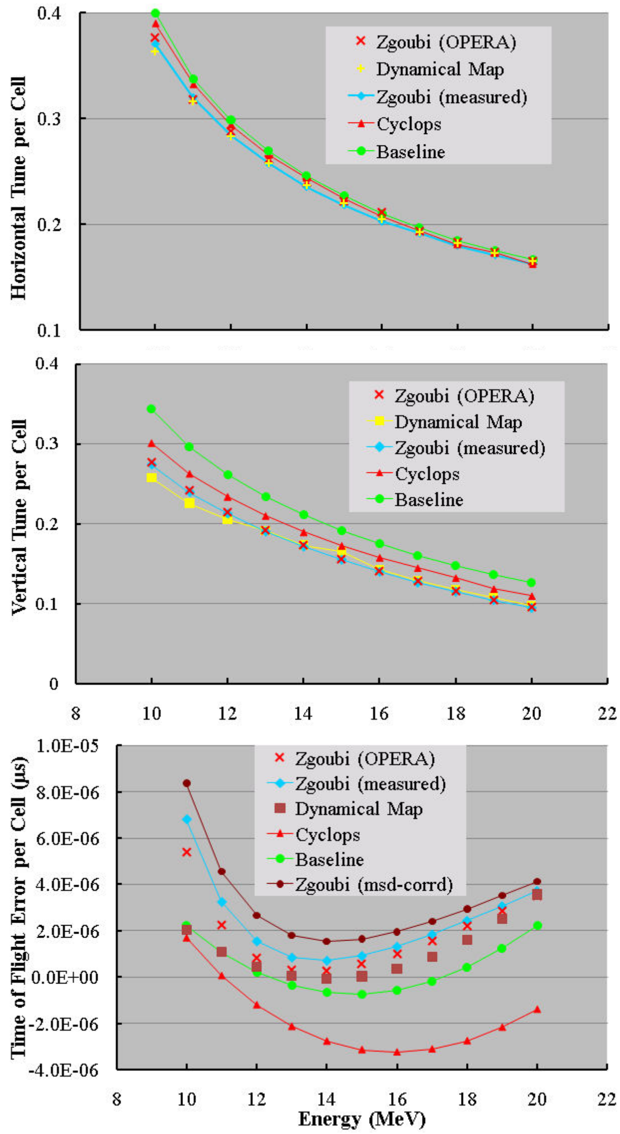

Figure 4: Tunes and time of flight error per cell in the measured EMMA field, as determined by various codes.

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. 5 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 [16]. For the measured field (bottom plot) the bunch distortion is greater and the beam gains less energy.

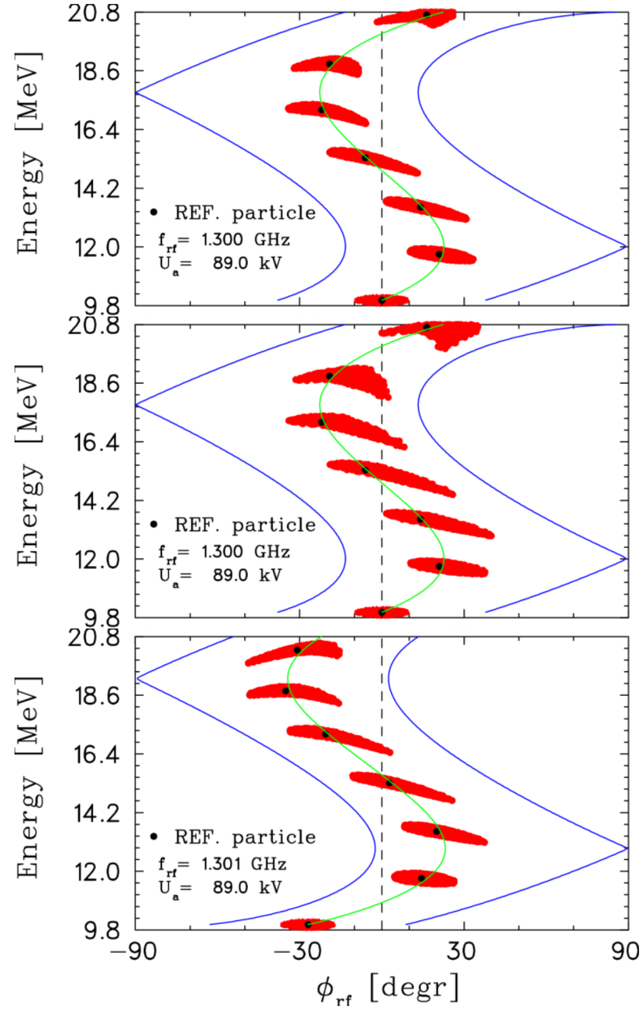

Figure 5: Energy-phase plots: (top) Baseline field, ε_x = 250π μm; (middle) Baseline field, ε_x = 1400π μm; (bottom) measured field, ε_x = 250π μm.

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