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PROGRESS ON SIMULATION OF FIXED FIELD ALTERNATING GRADIENT ACCELERATORS

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Abstract

Fixed Field Alternating Gradient accelerators have been realised in recent decades thanks partly to computational power, enabling detailed design and simulation prior to construction. We review the specific challenges of these machines and the range of different codes used to model them including ZGOUBI, OPAL, SCODE and a number of in-house codes from different institutes. The current status of benchmarking between codes is presented and compared to the results of recent characterisation experiments with a 150 MeV FFAG at KURRI in Japan. Finally, we outline plans toward ever more realistic simulations including space charge, material interactions and more detailed models of various components.

INTRODUCTION

Fixed Field Alternating Gradient (FFAG) accelerators have potential to provide high intensity hadron beams for various applications. This arises from the combination of strong focusing to reach high energies with a fixed magnetic field which enables a high repetition rate and high average current. In 2013 a collaboration was formed to focus effort in the FFAG community on this topic. The collaboration aims to undertake a series of experiments to progress toward high intensity operation of the 150 MeV proton scaling FFAG accelerator at Kyoto University Research Reactor Institute (KURRI) in Japan. Relevant parameters of the accelerator can be found in Ref. [1].

At the same time a simulation campaign has been established to benchmark relevant simulation codes. This campaign aims to provide reliable tools for FFAG modelling and to help understand the results of the experiments as they progress. After short description of the codes used, we will discuss present benchmarking efforts.

SIMULATION CODES

The beam orbit in an FFAG moves radially with momentum, as in a cyclotron. Simulation codes which assume a central orbit independent of momentum are unsuitable for studying FFAGs as they do not reproduce the correct dynamics. There are a few codes which remove the constraint of the existence of the central orbit: OPAL, Zgoubi, SCODE, MAUS and EARLIETIMES, which we have selected to perform our benchmarking.

OPAL

OPAL (Object Oriented Particle Accelerator Library) [2] is an open source C++ framework for general particle accelerator simulations including 3D space charge, short range wake fields and particle-matter interaction. OPAL is based on IPPL (Independent Parallel Particle Layer) which adds parallel capabilities. The main functions inherited from IPPL are: structured rectangular grids, fields, parallel FFT and particles with the respective interpolation operators. Massive parallelism (up to 65000 processors) makes it possible to tackle the largest problems in the field.

ZGOUBI

Zgoubi is a ray-tracing code which can track particles through electric and magnetic fields introduced as field maps or as analytic elements. It has excellent flexibility in the choice of elements, and includes complex geometries with high-order multipole and combined-function magnets as analytic elements. For this reason it has been adopted as one of the main simulation codes in the FFAG community [3].

SCODE

SCODE was developed specifically for the simulation of FFAG accelerators. Some of the modules such as the space charge module and the single particle tracking module with time as the independent variable are imported from another code, Simpsons [4]. Space charge calculation in 2.5D and frozen model are available. Simple models of multiple scattering in the transverse direction and energy loss due to foil scattering are also included. Recently, tracking based on 3D magnetic field maps has been added.

MAUS

MAUS (MICE Analysis User Software [5] is a tracking and reconstruction code base on Geant4 [6]. MAUS provides a framework for accelerator raytracing using custom field map routines, the Geant4 material physics libraries and the capability to plug-in realistic diagnostic modelling.

KURRI In-house Code EARLIETIMES

EARLIETIMES [7] was developed at KURRI for the purpose of design and beam commissioning of the KURRI FFAG accelerator complex. It uses a 4th order Runge-Kutta algorithm to find the closed orbit in a 3D magnetic field calculated by external software e.g. TOSCA. EARLIETIMES treats this closed orbit as a reference orbit, which can be

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distorted by some COD source, bump magnets, or other sources of perturbation. For long term tracking, a second order symplectic Lie transformation with respect to the reference orbit is available as well as the 4th order Runge-Kutta solver.

LOW INTENSITY BENCHMARKING

Setup of Benchmarking Model

Due to the relatively large gap height of the magnets and large extent of fringe fields compared with synchrotrons, a hard-edge model of the scaling FFAG lattice does not produce realistic beam dynamics, e.g. transverse tune and revolution frequency. In order to benchmark against experimental results, we use the 3D field map computed with TOSCA, as this is required to provide a basic description of the lattice.

The 3D TOSCA field map of one DFD triplet is computed with grid points in a cylindrical coordinate system typically every 1 cm. In the vertical direction, one grid layer is provided above and below the midplane, which gives the field gradient in that direction. The 3D field components at an arbitrary space coordinate are interpolated with the neighbouring grid points linearly (SCODE and EARLIETIMES) or with higher order interpolation (OPAL MAUS and Zgoubi).

We combine the 12 DFD cells that make up the ring and first compute the closed orbits at several momenta throughout the 11 to 150 MeV energy range. This provides the revolution frequency as a function of momentum, which allows us to construct a table of rf parameters (frequency and voltage) for acceleration. We then calculate optics properties such as beta and alpha function and tune.

Betatron Tunes

The first benchmarking was carried out for betatron tune. The TOSCA field map was calculated for excitation currents of 810A for the F magnet and 1020A for the D magnets, and imported into each of the different codes. The betatron tune as a function of momentum was then calculated. In the actual experiments there is large distortion of the closed orbit excited by the core material of the rf cavity absorbing the leakage field of the main magnets. In this study we take the ideal case by first comparing the tune with the assumption of 12 fold symmetry of the ring. In each code, the integration was optimised until the results became independent of step size.

Figure 1 shows the betatron tune with different codes. The agreement among the codes is excellent although there are slight deviations at the beginning and the end, which is due to poor interpolation at the first and the last grid points of the 3D map.

However, the betatron tunes from experiments at two different working points (Fig. 2) do not match well to the simulation. The 'EARLIETIMES' code for the same F/D ratio as used in the experiment is also shown for comparison. The particles appear to be trapped around resonances at several momenta, whose strengths are not properly included in the simulation.

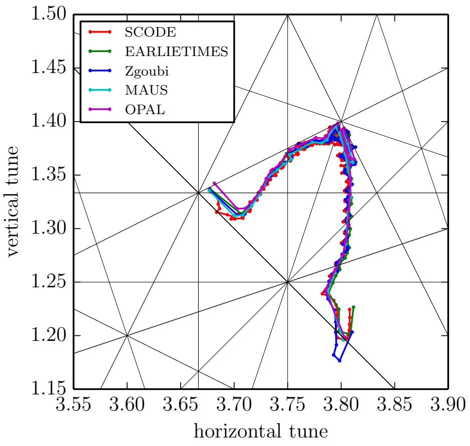

Figure 1: Betatron tune from 11 to 139 MeV calculated with SCODE, EARLIETIMES, Zgoubi, MAUS and OPAL.

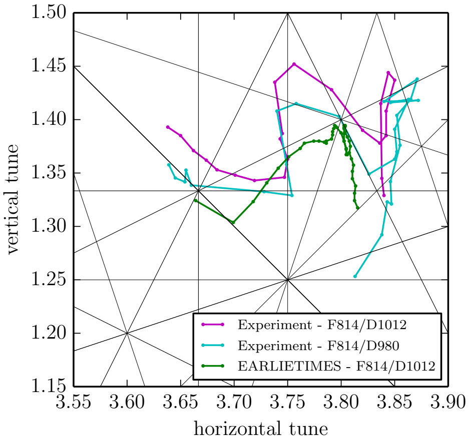

Figure 2: Measured betatron tune for two F/D ratios and simulation for comparison. Note the F814/D1012 data covers the range 11 to 100 MeV, while the F814/D980 data runs from 11 to 117 MeV.

To provide a more realistic lattice, closed orbit distortion due to a single kick at the rf cavity location was included on top of the 12-fold symmetry lattice. Originally it was assumed that the distorted orbit may pick up the non-linearities of the lattice differently in each cell and excite harmonics which are suppressed in the normal symmetric situation. Studies with SCODE shown in Fig. 3 do not, however, show any strong influence of the closed orbit distortion on the betatron tune.

There are a number of possible sources for this discrepancy between simulation and experiment. A deviation of the

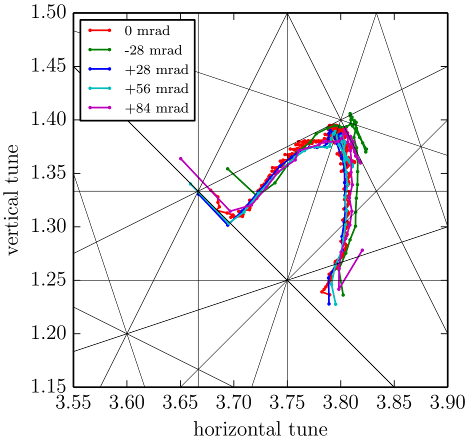

Figure 3: Betatron tune influenced by closed orbit distortion from various kick strengths at a single kick location.

magnetic field of the 12 main magnets from the design field map may already have existed before the introduction of the closed orbit distortion (COD). Alternatively, the existence of a vertical closed orbit distortion which was not included may be playing a role, or there may be an additional source of the horizontal COD. These items should be studied in future to make the simulations more accurate.

Accelerated Orbits with Variable Frequency RF

The second benchmarking exercise was carried out for longitudinal dynamics. The lattice based on the 3D field map complicates the momentum compaction factor, which depends on the position of the orbit. Correct modelling of acceleration is only possible taking into account the local momentum compaction factor accurately.

The first step in this benchmark is to obtain the revolution frequency *vs.* momentum relation. This was done by finding as many closed orbits as possible in the momentum range of acceleration. As seen in Fig. 4, all the codes give almost identical results.

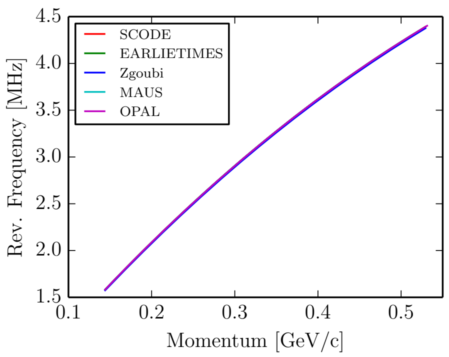

Figure 4: Revolution frequency vs momentum for kinetic energy range from 11 to 140 MeV.

The local momentum compaction factor (or the local slippage factor) is obtained as the derivative of this curve. By combining the rf cavity model and location of the rf cavity in the ring, the rf frequency and voltage as a function of time are calculated. Of course, this also depends on the rate of acceleration and the bucket area. In this benchmark, the synchronous phase, ϕ_s, is set constant at 30 degrees and the voltage is 4 kV throughout acceleration.

Particle tracking with acceleration is benchmarked with different codes and shown in Fig. 5. In the test case, the initial rf phase is 0 degree and there are synchrotron oscillation around $\phi_s = 30$. Again, both codes tested agree with each other.

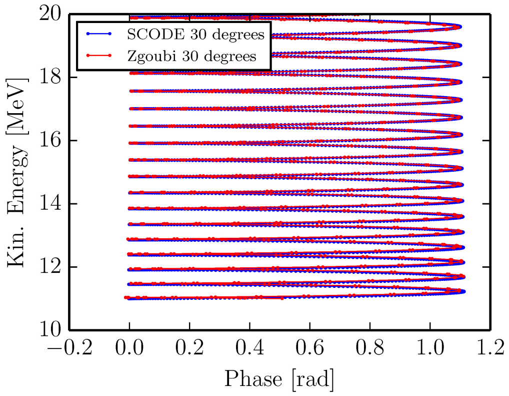

Figure 5: Single particle with acceleration comparison of Zgoubi and SCODE.

HIGH INTENSITY AND FUTURE PLANS

Based on the successful low intensity benchmarking of single particle dynamics, the next step in the benchmarking process will be to look at beam emittance evolution with space charge effects. The model of space charge in the different codes is not the same and thus is not expected to have identical behaviour.

In order to accumulate and accelerate a large number of particles, charge exchange injection is essential. The KURRI 150 MeV FFAG employs an H- linac and injects the beam using charge exchange injection through a carbon stripping foil. FFAGs in principle do not need pulsed magnets for an injection bump orbit because the orbit moves outward as the beam is accelerated. On the other hand, without sufficient acceleration voltage, the beam circulates through the foil for a long period. Multiple scattering and energy loss at the foil could deteriorate beam quality if the injection process is not optimised. This injection process also needs to be simulated and benchmarked. Most of the codes mentioned herein have modules to include this material interaction process. Detailed simulations combining space charge and foil modelling will be pursued.

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