Bmad MODEL OF COSY, STATUS AND PROGRESS

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Abstract

The COSY[1] in Jülich is a versatile machine with a long history of polarized proton acceleration. A new model of COSY based on the Bmad library was developed to simulate beam and spin dynamics. Original methods of lattice design, notably multi-objective lattice optimization, were explored.

This contribution presents the status and development steps of the Bmad model of COSY. Some of the latest simulations will also be discussed.

INTRODUCTION

In recent year, a strong effort has been made around the COSY machine and the COSY team towards precise measurement of the EDM [2] of deuteron and proton. Such measurement will not be discussed directly here but it is commonly agreed that robust and particularly accurate simulation tools for beam and spin dynamics are required in this context.

Currently, modelling of the COSY online optics uses the MAD8 code. Although particularly robust the code does not include spin dynamics and the choice of available elements is limited. Simulation of complex fields, such as the ones encountered around the COSY electron cooler, can be hard to implement in the MAD8 matrix formalism. Modelling of spin dynamics in COSY is using the COSY infinity code. This code is particularly fast and accurate but will not be discussed here.

The Bmad code was proposed to simulate the COSY ring for both spin dynamics and beam dynamics, eventually towards online modelling. Bmad is a Fortran90 library providing an environment to define and manipulate electromagnetic lattices or optics and to track particles [1].

Bmad MODEL OF COSY

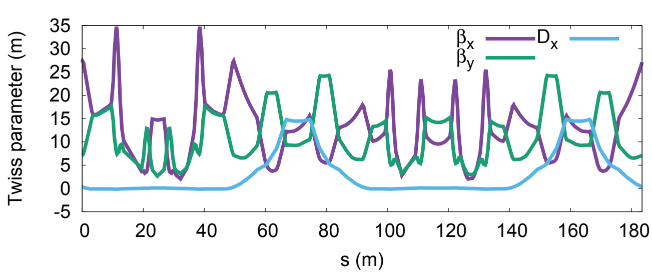

Figure 1: Plot of the Twiss parameters along the COSY ring.

The first step was to convert the MAD8 lattice of COSY into the Bmad syntax. The syntax are very similar between the two codes but major changes were still required, mostly due to the fact that the Bmad lattice is read but not interpreted.

[1] COoler SYnchrotron
[2] Electric Dipole Moment

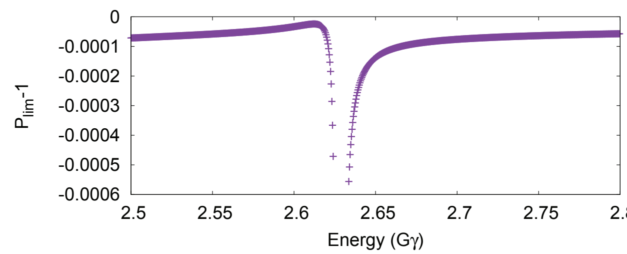

Figure 2: Plot of maximum time-average polarization minus 1 of a proton with a vertical normalized invariant of $10\,\pi$ mm mrad, as a function of the energy.

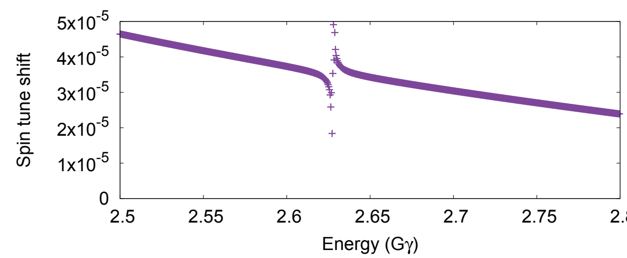

Figure 3: Plot of spin tune shift of a proton with a vertical normalized invariant of $10\,\pi$ mm mrad, as a function of the energy.

Other changes were made to facilitate manipulation and comprehension of the lattice files. Namely, different aspects of the lattice were split in different files :

- **COSY.bmad** : initializes variables such as the species or the beam rigidity.
- **COSY_bend_errors.bmad** : contains the quadrupole and sextupole components, measured, of the COSY dipoles.
- **COSY_magnet_settings.bmad** : contains the definition of all the elements of the COSY ring.
- **COSY_layout.bmad** : contains the sequence of element constituting the COSY ring.
- **COSY_controllers.bmad** : defines a special Bmad element (*overlay*) used to control other elements of the COSY lattice in order to easily vary strings of magnets sharing a power supply. Here 8 overlay control the straight sections quadrupoles, 6 the arcs quadrupoles and 3 for the 3 arcs sextupole families.

Figure 1 shows the Twiss parameters along the COSY lattice in its usual experimental optics. In this case particular case the lattice tunes are $(3.62, 3.63)$ respectively for the horizontal and vertical planes, without sextupoles the chromaticities are $(-4.92, -3.75)$ and the transition energy

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is $\gamma_{tr} = 2.25$. In this configuration one can see that the horizontal dispersion is null in the two straight sections. Agreement between the MAD and Bmad models is perfect but that is to be expected since Bmad can use the same formalism as MAD, which was the case here.

The Bmad library contains numerous functions to compute quantities such as Twiss parameters or chromaticity. However spin dynamics studies often require other specific tools and algorithms, not included in the Bmad distribution.

The first development was a code to compute the stable spin direction at any point of the 6-D phase space. I implemented in Fortran90 using Bmad a version of the *Reverse Forward Tracking* algorithm derived from the stroboscopic averaging and first introduced in [2]. Figure 2 shows the evolution of the maximum time-average polarization (P_{lim}) as a function of the energy of the lattice described above. The main features is the drop around $G\gamma = 2.6$, a clear sign of depolarizing resonance, associated here to the intrinsic spin resonance $G\gamma = Q_y - 1$.

Then I implemented a function capable of computing the amplitude dependent spin tune on a given phase space trajectory. The code tracks a single particle for a large number of turn, typically 1000. The spin motion is then frequency analyzed using a NAFF algorithm that extract the spin tune frequency. Figure 3 shows a strong discontinuity around $G\gamma = 2.6$, characteristic of a strong depolarizing spin resonance.

These tools establish the basis of all subsequent spin studies, and in particular the ones presented here.

SPIN TUNE SPREAD

As mentioned in the *Introduction* the measurement of the EDM (proton and deuteron) is a major project for the COSY team. Although the final design of the experiment is not settled yet it will most likely involve the beam polarization to be maintained in the horizontal plane. This is challenging since the precession axis is dominated by the dipole, vertical magnetic field. It results in the spin tune spread within the beam to be a source of beam polarization loss, unlike when the beam polarization is aligned with the stable spin direction. Minimization of the spin tune spread within the beam is therefore critical.

The source of the spin tune spread is, in essence, similar to the spread of transverse tune for beam dynamics. Particles experience different fields, acting on the spin vector, due to different trajectories.

Some effects can be isolated, such as the effect of the path lengthening. Particles of different transverse invariants are associated with different path length per turn. The use of an RF cavity constraints the revolution frequency of all the particles hence shifting the reference energy of particles within the beam. This contributes to the spin tune spread and had been studied.

Figure 4 shows the effect of the path lengthening, using the same particle and lattice conditions as earlier. A single particle is tracked at different amplitudes with $\epsilon_x = \epsilon_y$. As

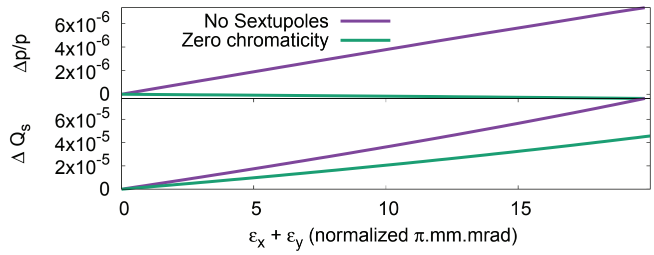

Figure 4: Shift in the equilibrium relative momentum as a function of the summed transverse emittances (top plot) and associated spin tune shift.

expected the equilibrium momentum is shifted as a function of the particle amplitude due to the path lengthening effect and the RF cavity. This effect is dramatically reduced when the lattice chromaticity is adjusted to zero using sextupoles, as predicted in [3]. However the bottom plot shows that the effect on amplitude dependent spin tune is much weaker. Although chromaticities close to zero minimizes the path lengthening effect it also introduce numerous non-linear fields acting on the spin. Therefore the minimization of the path lengthening effect cannot, alone, minimize the spin tune spread.

The optimization of the spin tune spread is a complex problem that cannot be reduced to a single, simple, effect. The parameter space of possible variables acting on the spin tune spread contains all the machine variables, which is too large of a systematic simulated scan. This call for the use of advanced optimization tools capable of find a global minimum in a large parameter space.

EVOLUTIONARY OPTIMISATION OF THE SPIN TUNE SPREAD

Optimization of the spin tune spread is achieved in the complete parameter space containing 14 quadrupole families, 3 sextuple families and 7 independent sextupoles. Such a large parameter space cannot rely on classical minimization algorithm to find a global minimum. The best alternative would have been to apply a brute force grid search. However the parameter space is too large with 24 dimensions.

I implemented an evolutionary algorithm to minimize the spin tune spread, using the DEAP [4] Python library. In this context solutions are refereed as individuals and machine parameters as genes. The algorithm follows the usual steps :

- *Initialization*, to generate an initial population. I start with a few stable lattices, typically at different tune working point and with different chromaticities setting.
- *Evaluation*, to estimate the fitness of each individual. This generally involve tracking of a group of particles to probe the behaviour of the amplitude dependent spin tune in the 6-D phase space. The method being intrinsically multi-objective other quantities can be used to evaluate the fitness. In the next examples the distance between the transverse tunes and the distance from the

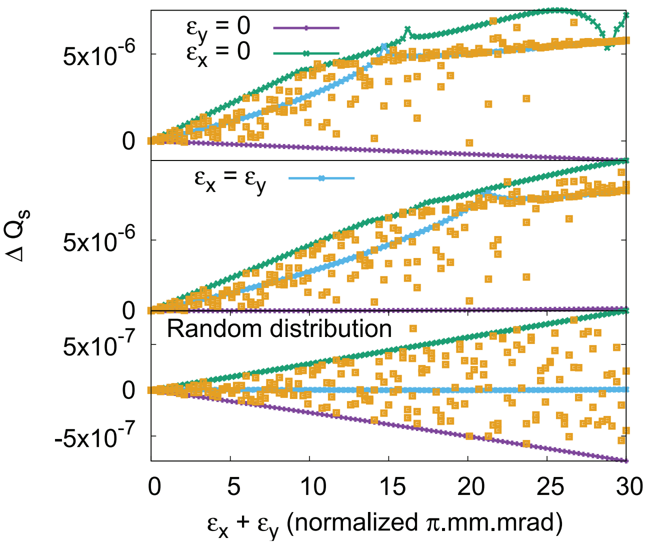

Figure 5: Spin tune shift of deuteron beam for particles at different amplitudes as a function of the sum of the transverse amplitudes for different lattices. Without sextupole for the top plot, with zero chromaticity on the middle plot and with optimized lattice for the bottom plot.

tune working point to the closest coupling resonance are also used.

- *Selection*, to select the set of individuals to survive. This is a particularly delicate step where the choice of the selection tool is critical. In particular in the case of multi-objective minimization, simple selection of the best individuals can be non-optimal compare to tournament based selections.
- *Crossover and mutation*, to breed and mutate the selected individuals. This step generates a new population by breeding and random gene alteration of the selected individuals. This step is very sensitive and might require numerous test to find the right combination of crossover method and probabilities as well as mutation strengths and probabilities.

Figure 5 shows a representation of the spin tune spread. The amplitude dependent spin tune shift is determined for different particles. Namely, a particle with only horizontal or vertical amplitude, with amplitudes equal in both planes and with random amplitudes in both planes. The representation of those data as a function of the summed amplitude of the two transverse planes gives a good qualitative view of the spin tune spread within the beam. In this particular case the first two plots show a distorted behaviour, particularly for particles with non-zero horizontal amplitudes. This is due to beam dynamics problems since the lattice features tunes very close to one another and close to the 3^{rd} order resonance line.

We can see that the lattice featuring zero chromaticities, experiences a lower amplitude dependent spin tune shift for particles without vertical amplitudes. However the spin tune shift for particles with only vertical amplitude the spin tune shift is slightly increased. The last effect can certainly be attributed to the effect of the sextupoles used to reduce the chromaticities.

Finally the lattice fully optimized shows much lower spin tune spread. The bottom plot on Figure 5 shows the amplitude dependent spin tune shift for the optimized lattice. The dependence of the spin tune to the transverse amplitude is much lower than for the other lattices. Additional the figure is perfectly centred around zero, allowing amplitude dependent spin tune shift due to vertical amplitude to compensate with the one due to horizontal orbit. This is a configuration that the evolutionary algorithm always seems to converge towards.

CONCLUSION

The optimized lattice features a very small spin tune footprint but with a tune working point of (3.84, 2.59) and chromaticities of -3 and -14 respectively in the horizontal and vertical planes. Those parameters are very far from usual conditions and might not even be realistic from a beam dynamics point of view.

However, any constraints can be added to the evolutionary algorithm. Experimental limitations such as the magnets capabilities or the machine apertures were ignored here but should certainly be included for a comprehensive study.

In any case, the use of an evolutionary algorithm for optimizing the spin tune spread was proven to be useful. We have shown in particular that some optimal solution can be very far from normal machine conditions.

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