DESIGN STUDY OF COMPACT CYCLOTRON MAGNET IN VIRTUAL PROTOTYPING ENVIRONMENT *

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Abstract

An intelligent magnet design, modelling and optimization method with the aid of beam dynamics analysis and three dimensional magnetic field calculation is introduced. The whole procedure is implemented in an integrated virtual prototyping environment built with python language. As a case study, the main magnet design of a 16MeV H^- compact cyclotron is illustrated. Both the field isochronism and transversal focusing of the beam can be fulfilled, and the mechanical analysis is performed to validate the feasibility in mechanics.

INTRODUCTION

Virtual prototyping (VP), a novel engineering technique, provides a continuous development environment for products. By evaluating virtual prototypes, it can reduce or replace the real physical prototypes, thus saves the cost and time-consuming of products' R&D. We have applied VP technique to the design and development processes of low-energy cyclotrons, and the framework of cyclotron VP platform (CVPP) has been proposed [1].

The primary goal of CVPP is to provide an integrate environment for multiple design or analysis components covering beam dynamics, magnet, RF cavity, injection line and control system etc. Virtually these modules are heterogeneous. They are written in different languages such as FORTRAN, C and C++. And some of them are commercial software. How to encapsulate these modules and establish an effective inter-communication method becomes a key issue. The agent based approach with CORBA is a conventional but complicated solution, which requires a long development period. Nowadays, using the high level scripting languages such as Python or Perl becomes an increasingly popular approach to scientific computing [2]. In our solution of CVPP, Python language was used to build the user interface and to be a powerful 'code gluer' for integrating different VP modules [3].

As a crucial task in cyclotron design, main magnet design and optimization includes iterative processes from an initial crude model. The optimized magnetic field distribution should fulfil requirements of isochronisms and transversal focusing of the beam, as well as to avoid dangerous resonance crossing. This paper mainly introduces an automated magnet design, modelling and shimming method under the pythonic integrated environment based on virtual prototyping. The detail magnet shimming processes with the support of the 3D magnetic field simulation code TOSCA [4] and an original developed particle tracking code PTP are described.

MAGNET DESIGN AND OPTIMIZATION PROCESSES

The isochronous average magnetic field of cyclotrons should increase with radius:

$$B_{iso}(r) = \gamma(r)\cdot B_c = (1+T/E_0)\cdot B_c \qquad (1)$$

Where B_c is the magnetic field in the center of the cyclotron , T is the kinetic energy of ions, and E_0 is the rest mass energy.

In low-energy compact cyclotrons, a common method to achieve the isochronous field is to increase the ratio of hill/valley along radius, which called magnet shimming. CVPP takes this method to design the main magnet of cyclotrons.

The magnet optimization is automated in CVPP with the collaboration of *magnet design module* and *beam dynamics analysis module,* as shown in Figure 1.

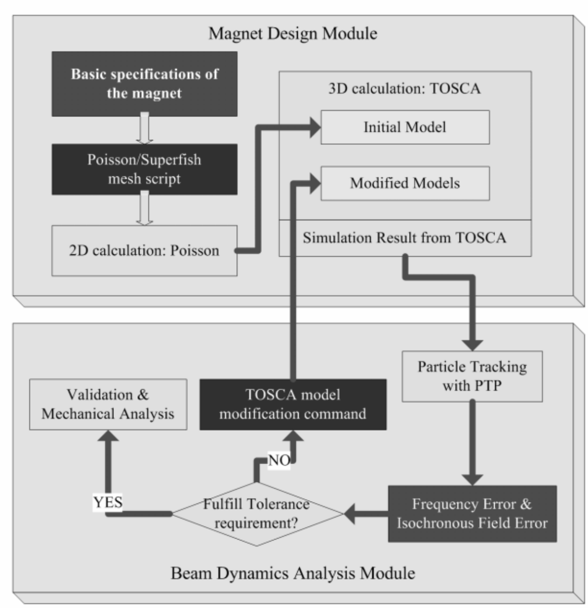

Figure 1. Automated magnet design and optimization process

Based on some basic magnet specifications and 2D calculation result, an initial 3D magnet model is constructed in OPERA-3D and the magnetic field is

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simulated with TOSCA solver. Then, the *magnet design module* of CVPP takes some procedures to find an isochronous magnet model from this initial one:

Step 1. Magnetic Field Error Calculation:

PTP (Particle Tracking Package) is an beam dynamics analysis code written in C++, which can track particles in field map from calculation or measurement. By searching the equilibrium orbits at different particle kinetic energy, it can calculate the frequency error $\Delta f_p(r)$ relate to the design cyclic frequency f_p. By using equation (2), the isochronous magnetic field error can be estimated [5].

$$\Delta B(r) = B_{iso}(r) \cdot \gamma^2(r) \cdot \Delta f_p(r) / f_p \qquad (2)$$

Step 2. Magnet Model Correction:

The hard-edge magnet model was used to give an approximate solution to convert magnetic field error to corresponding sector angle error, as shown in equation (3).

$$\Delta\eta(r) \approx \Delta B(r) \cdot \frac{2\pi/N}{B_H(r) - B_V(r)} \qquad (3)$$

$B_H(r), B_V(r)$ are magnetic field in hill and valley of the magnet pole, N is the sector number of magnet. $\Delta\eta(r)$ is the corresponding sector angle change due to the magnetic field error $\Delta B(r)$. Usually, $\Delta\eta(r)$ used for model correction need to be multiplied with a experience factor σ with the value between 0.5~0.9 to avoid oscillation of field error during iteration.

The magnet sector angle can be regulated by modifying the control points of the shimming bar attached to the magnet pole. The *magnet design module* calculates an angle correction list along the radius and generates a model transformation command file for OPERA pre-processor. Thus one complete shimming process is finished. The simulation result of this modified model is checked again in *step 1* until the tolerance is achieved.

Step 3. Model Validation and Mechanical analysis:

When the isochronous magnetic field error is small enough, this validation step starts. PTP will calculate local phase slip to make sure the total phase slip is well controlled. Also, horizontal tune and vertical tune during acceleration is calculated and beam focusing should be satisfied in the magnetic field. If the working point is near the dangerous resonance line or slow resonance crossing happens, the structure of the magnet need to be revised and optimized. Finally, the mechanical analysis including deformation and von Mises stress distribution should be performed.

A CASE STUDY: MAGNET DESIGN OF A 16 MEV H$^-$ CYCLOTRON

A virtual magnet prototype of a 16MeV H$^-$ cyclotron is built for illustration. The main specifications of the magnet are shown in table 1.

Table 1: Magnet Specifications of 16MeV H$^-$ Cyclotron

Parameters	**Value**
Number of sectors	4
Sector angle	50 degree
RF frequency	80.2 MHz
Harmonic mode	4
Average Magnetic Field	1.35 T
Hill / Valley gap	0.03 / 0.40 m
Extraction radius	0.44m

The initial magnet sector model is shown in fig. 2. One simple straight shimming bar are attached to the side of magnet pole. The shimming bar is parameterized with 20 modifiable edge points.

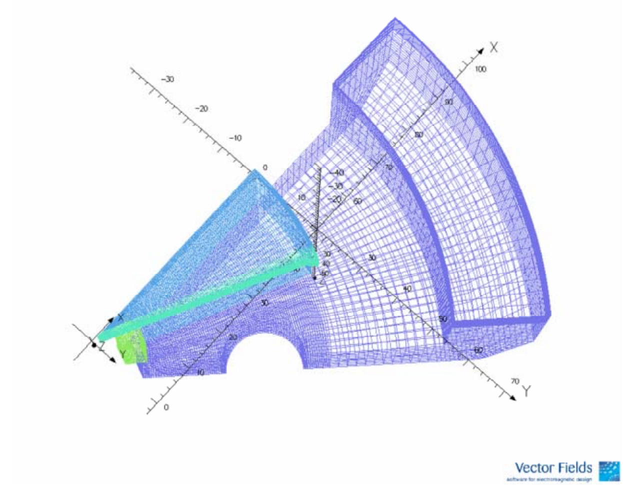

Figure 2. 1/16 parametric magnet model.

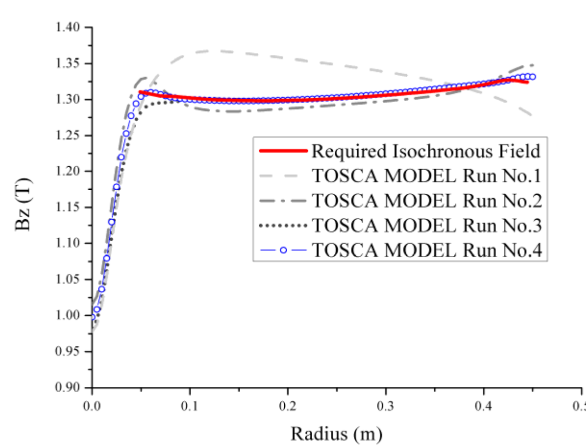

Figure3: Average magnetic field compared with required isochronous field during iterations.

After 4 automated iterations, the magnetic field satisfies tolerance of isochronisms. The TOSCA simulated average magnetic field during iterations and the required isochronous field is shown in figure 3. Figure 4 shows the final shape of the shimming bar comparing to the initial model. For the optimized model, the orbital frequency error is controlled within 0.1%, and the total phase slip is about 5 degree.

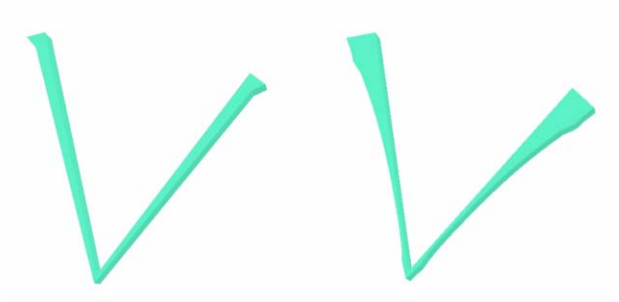

Figure 4: Models of the initial shimming bar and the optimized one after 4 iterations.

Fig. 5 shows the tune diagram during acceleration. As can be observed, both radial and vertical tune are stable. Integer, half integer and Walkinshaw resonance crossing are avoided.

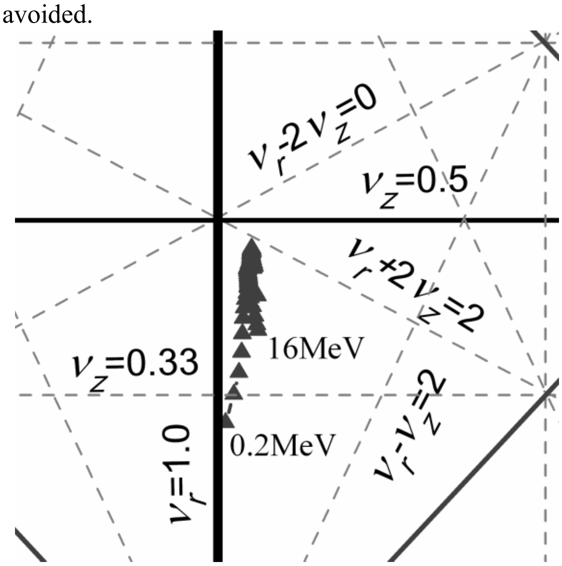

Figure 5: Tune diagram.

The mechanical analysis is important for estimating magnetic field varying due to deformation. The results also can be used to judge whether the von Mises stress exceeds the yielding stress.

Firstly the magnetic force between magnet poles is calculated by TOSCA. In this case, it is 151.6 kN for each sector pair. Mechanical analysis can be performed by taking magnetic, gravitational and vacuum forces as loads. As shown in figure 6, the maximum deformation in pole surface is 65 μm at the position of radius 5cm, with the contribution to the magnetic field error about 0.065/15 = 0.4%. This error can be corrected easily by magnet shimming. Figure 7 shows the maximum von Mises stress is 23 MPa when the cyclotron is working. The stress is far below the yielding stress, which proves this design is feasible and safety for mechanics consideration.

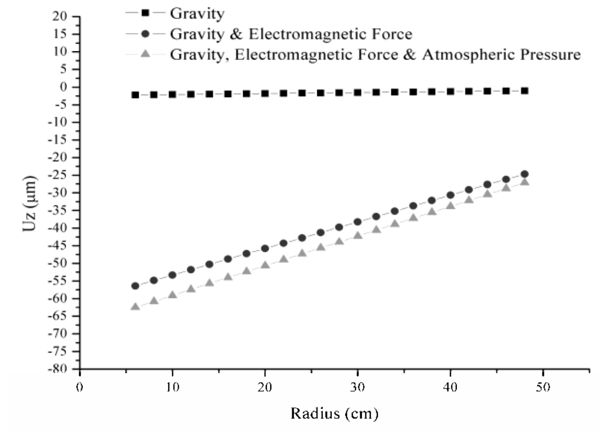

Figure 6: Deformation in the central line of magnet pole surface with different conditions.

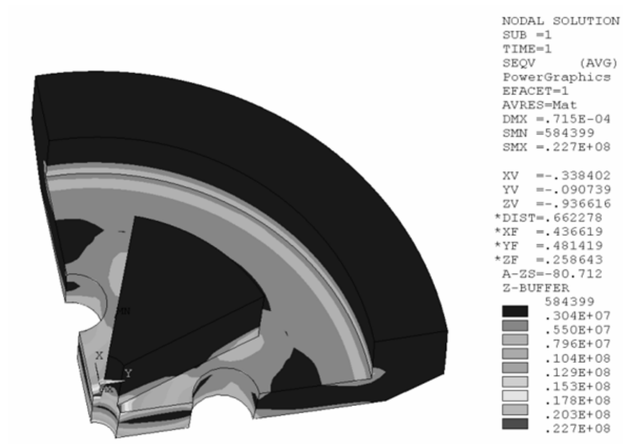

Figure 7: Von Mises stress distribution

CONCLUSION

This paper described a systematic method for the modeling and correction of the magnet of cyclotrons in the framework of CVPP. The method is validated by virtual magnet models and also can be applied to the magnet measurement and shimming process during construction of cyclotrons.

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