第19卷 第4期
2007年4月

强激光与粒子束
HIGH POWER LASER AND PARTICLE BEAMS

Vol. 19, No. 4
Apr., 2007

Article ID: 1001-4322(2007)04-0689-06

Magnet design and shimming of cyclotrons based on virtual prototyping*

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Abstract: Magnet design and modeling is a crucial task in the design of cyclotrons, which includes iterative processes from an initial model. The magnetic field distribution should fulfill the requirements of isochronisms and transverse focusing of the beam, as well as avoiding dangerous resonance crossing. This paper introduces an automated magnet design, modeling and shimming method under the pythonic integrated environment based on virtual prototyping, a novel technique to shorten development period and reduce costs for physical prototypes. Detailed magnet shimming processes with the support of the 3D magnetic field simulation code TOSCA and an original developed particle tracking code PTP are described. As a case study, the main magnet design of a 16 MeV H^- compact isochronous cyclotron is illustrated and validated in a virtual prototype.

Key words: Magnet shimming; Cyclotron; Virtual prototyping; Python language

CLC number: TL542.1 **Document code**: A

As a novel application of Virtual Reality(VR), Virtual Prototyping(VP) has been developed since 1990s with the increasing demand for research and development(R&D) of products in a short period and in a cost effective manner[1]. Furthermore, VP provides an integrated environment in which the design, development, manufacture and operation can be studied and controlled in an interactive method. Virtual prototypes can reduce or replace the use of physical prototypes, thus decreases the expenses of products ' R&D.

In areas of nuclear instruments like accelerators, virtual techniques have been applied in some projects. The Navigation in the Underground Sites system(VENUS)[2] was developed in CERN for the design of Large Hadron Collider(LHC), which helps engineers to understand the work process and complex structure of LHC. KEK employed the concept of" Virtual Accelerator "to develop the control system of KEKB[3].

We applied VP technique to the design and development of compact isochronous cyclotrons[4-5], which conduces to generating innovational schemes and reducing risks. To establish an integrated environment for VP of cyclotrons, effective software architecture is required foremost. By combining powerful scripting python language and mixed-programming technique, the Cyclotron VP Platform(CVPP) was implemented with a distributed framework. CVPP encapsulates various VP sub-components covering magnet design, RF system design, beam dynamics analysis and control system simulation, etc.

Magnet design is one of the most important issues in the design of isochronous cyclotrons. Foremost it requires a global view of cyclotrons because interactions with other sub-systems like RF cavity and vacuum system should be considered. CVPP provides a top-down design environment to take such restrictions into account and avoid conflicts at the early design phase.

The main target of magnet design is to provide isochronous field distribution during particle acceleration and enough radial and axial focusing of the beam, and to avoid dangerous resonance crossing during acceleration. Normally, to achieve these conditions, iterative procedures need to be executed from a rough initial magnet model[6].

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* **Received date** 2006-12-21; **Revised date** 2007-04-12
Foundation item Supported by the National Natural Science Foundation of China(10435030)
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Magnet shimming normally refers to the correction of the pole shape after manufacturing and assembling of the magnet[7]. In this paper, we extend “shimming” to virtual magnet prototypes. Under the framework of CVPP, automated modeling and shimming is implemented with the aid of OPERA-3D/TOSCA simulation and particle tracking method.

1 Framework of CVPP based on the scripting language Python

1.1 Python language and mixed-programming

Python is an object-oriented interpreted language, which combines remarkable power with elegant syntax and high-level built-in data types. Due to unique concise syntax and full system-level functions, Python is very suitable for software system integration and can be used as a powerful “code gluer”. Numerous open-source Python modules covering areas of GUI, numeric computing, network and database extend Python to extensive applications. User written Fortran/C/C++ codes can also be compiled to Python modules with the aid of SWIG (simplified wrapper and interface generator)[9].

The Tkinter module is a standard Python interface to the Tk GUI toolkit. Both Tkinter and Tk are available on most Unix, Macintosh and Windows systems, which offer a native look and feel GUI.

CVPP is a typical software system for scientific computing. Mixed-language programming, which combines script language like Python and compiled language such as Fortran/C++, is becoming an increasingly popular approach to scientific computing. Such a method merges the high computing performance with a flexible and easy-to-extend interpreted language.

1.2 Framework of CVPP

By employing Python language and mixed-language programming, the framework of VP integrated platform was established, as shown in figure 1. The framework divides the platform into two parts: basic scenario and upgrade components.

The basic scenario covers all essential VP design components of cyclotrons. The Beam Dynamics Analysis Module is located at a local server, and the other components including the Magnet Design Module, the RF Design Module are distributed as clients. The client components are located at different network computers or at the same site of the master server. For simplicity of code implementation, commands and data files based on TCP/IP socket are used for inter-communication between components. By using a Python/Tkinter HMI, cyclotron designers can access to various VP modules easily. Each module might contain some sub-modules or codes implemented by different program languages like C++ and Fortran. They can be wrapped into Python modules by SWIG tool, or be called directly with command/script input.

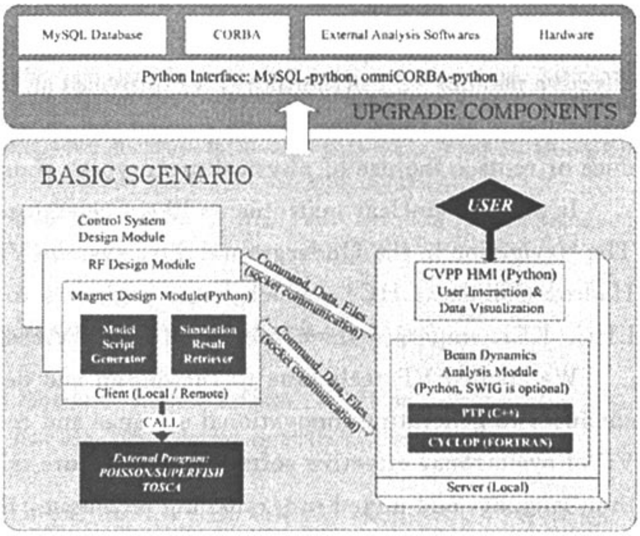

Fig. 1 Framework of CVPP

Upgrade components are designed for advanced software architecture. In the future, VP of cyclotrons will become more complex and socket communication might not meet the requirements. Two Python extended modules are used: omniCORBA-Python provides an interface to CORBA, a widely used distributed system architecture; and MySQL-Python supplies the Python implementation of MySQL database system. These features render the platform more expandable. Some accelerator design codes can be integrated into this platform.

2 Automated magnet modeling and shimming

The isochronous average magnetic field of cyclotrons increases with the radius

$$B_{\mathrm{iso}}(r) = \gamma(r) B_{\mathrm{c}} = (1 + T/E_0) B_{\mathrm{c}} \tag{1}$$

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.

There are three major methods to maintain the isochronous field in AVF cyclotrons, (1) To increase the angle ratio of hill/valley when the radius grows; (2) To use trim coils, which brings complexity; (3) To decrease the pole gap when the radius grows, but this will lead to lower beam intensity and is more difficult for machining. CVPP takes the first method to design the magnet for low-energy compact cyclotrons.

The automated magnet design and shimming process is mainly implemented by the collaboration of the Magnet Design Module and the Beam Dynamics Analysis Module in CVPP, as shown in fig. 2. Some procedures are taken to achieve an isochronous magnet model from a simple initial shape.

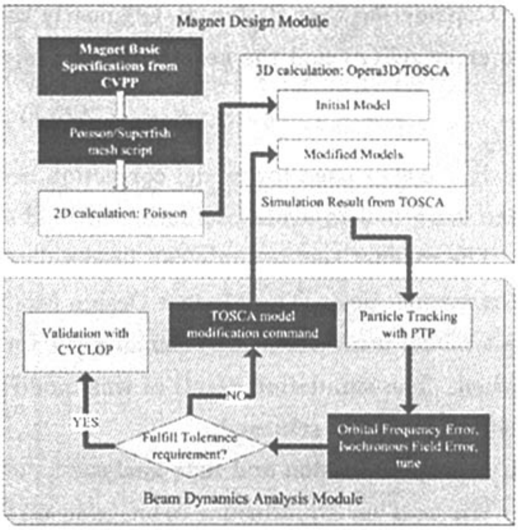

Fig. 2 Automated magnet design and shimming process with the collaboration between magnet design module and beam dynamics analysis module of CVPP

2.1 Magnet modeling and simulation

When the ions type and extraction energy are given, CVPP can estimate the basic specifications of the magnet, such as dimensions, gap size and current density. From this information, the Magnet Design Module generates mesh script and call Poisson[10] code to validate the preliminary model.

Based on the 2D calculation result, an initial 3D magnet model is constructed. By using 3D magnetic field simulation code TOSCA[8], field map is calculated out and transmitted to the Beam Dynamics Analysis Module for particle tracking. For the TOSCA simulation result is accurate enough to approach to the real magnetic field distribution, the tracking result is also reliable.

2.2 Magnetic field error calculation

Particle Tracking Package (PTP) is an originally developed C++ code, 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 $\Delta f_{\mathrm{p}}(r)$ relating to the design constant rotation frequency of particles f_{p}.

Equation (2) shows a quick route to estimate magnetic field error $\Delta B(r)$[6].

$$\Delta B(r) = \frac{\gamma^2(r)\,\Delta f_{\mathrm{p}}(r)}{f_{\mathrm{p}}} B_{\mathrm{iso}}(r) \tag{2}$$

2.3 Magnet model correction

The frequency error and field error are unacceptable for the initial model. Magnet model needs to be corrected from the current calculated errors. Generally speaking, the frequency error should be limited within 0.1% and the magnetic field error should be controlled to several gauss.

The hard-edge magnet model is used to give an approximate solution to convert magnetic field error to corresponding sector angle error. As shown in fig. 3, $B_{\mathrm{H}}(r)$ and $B_{\mathrm{V}}(r)$ represent the maximum and minimum values of the real flux density, η is the angular width of the hard edge field model which

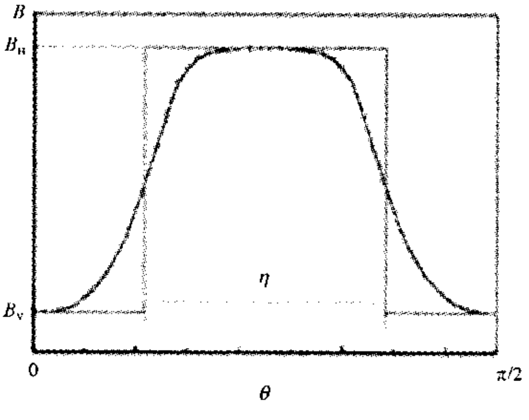

Fig. 3 1/4 Hard-edge magnet model (sector number $N=4$)

equals to current sector angle. The average field is given as

$$B(r) \approx \frac{B_H(r)\eta + B_V(r)(2\pi/N - \eta)}{2\pi/N} = B_V(r) + \frac{[B_H(r) - B_V(r)]}{2\pi/N}\eta \tag{3}$$

here N is the sector number of magnet.

Considering that $B_H(r)$,$B_V(r)$ nearly keep constant with a small change $\Delta\eta(r)$, the relation between the field error $\Delta B(r)$ and the sector angle change $\Delta\eta(r)$ can be given as

$$\Delta B(r) \approx \frac{[B_H(r) - B_V(r)]}{2\pi/N}\Delta\eta(r) \tag{4}$$

Usually, $\Delta\eta(r)$ used for model correction needs to be multiplied with an empirical 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 by magnetic field error calculation until the tolerance is achieved.

2.4 Model validation and tune analysis

We uses an equilibrium orbit code CYCLOP[11] developed by TRIUMF to validate the final modified magnet model. Also, horizontal tune and vertical tune during acceleration are 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 needs to be revised and optimized.

3 Particle tracking

Particle tracking is necessary to estimate the isochronisms and calculate the field error. An originally developed C ++ code PTP is utilized for this purpose.

PTP employs 4th order Runge-Kutta integration method to trace particles in the magnetic field map with the following differential motion equations(6) derived from equation(5) in the cylindrical coordinate system.

$$m\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = q(\boldsymbol{v} \times \boldsymbol{B}) \tag{5}$$

$$\begin{cases} m\mathrm{d}v_r/\mathrm{d}t = qv_tB_z - qv_yB_t + mv_t^2/r \\ m\mathrm{d}v_t/\mathrm{d}t = qv_zB_r - qv_rB_z - m(v_t/r)v_r \\ m\mathrm{d}v_z/\mathrm{d}t = qv_rB_t - qv_tB_r \end{cases} \tag{6}$$

To keep the same integration steps with different particle energy, it is convenient to take the azimuthal angle θ as the independent variable replacing time t with conversion equation

$$\mathrm{d}t = r\mathrm{d}\theta/v_t \tag{7}$$

Betatron tune can be calculated by employing Fast Fourier Analysis(FFT) on particle 's relative position to the equilibrium orbit with multi-turn tracking. PTP is also able to trace beam particles and estimate beam dynamic aperture.

4 Example and validation

For illustration of the automated magnet shimming procedure, we established a virtual magnet prototype of a 16 MeV H$^-$ compact cyclotron under CVPP. Table 1 shows the main specifications of the magnet.

Table 1 Specifications of 16 MeV H- cyclotron

injection energy/KeV	extraction energy/MeV	number of sectors	sector angle /(°)	RF frequency /MHz	harmonic number	average field/T	hill-valley gap/m	extraction radius/m
25	16	4	50	80.2	4	1.35	0.03 / 0.60	0.44

The initial magnet sector model is shown in fig. 4. For the sector number is 4, only 1/8 magnet is modeled. Two simple straight shimming bars are attached to the side of magnet pole, the shape of which is controlled by modifying the coordinates of 20 edge points.

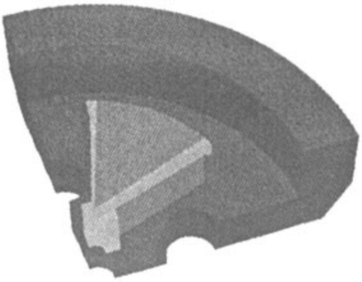

Fig. 4 1/8 TOSCA magnet model with meshes

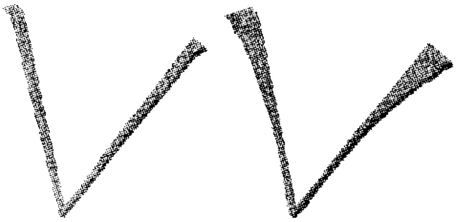

Fig. 5 Initial straight shimming bar and the final shape after 4 iterations

It is obvious that the field map calculated from the initial model can not meet the isochronous condition. After 4 automated magnet shimming iterations in the magnet design module of CVPP, the magnetic field satisfies the tolerance of the isochronisms. Fig. 5 shows the final shape of the shimming bar comparing to the initial model. The TOSCA simulated average magnetic field and the required isochronous field are shown in fig. 6.

CYCLOP is used to validate the revised model and calculate betatron tune. Fig. 7 shows the frequency error of particle rotation calculated by PTP and CYCLOP. The results agree well, and the orbital frequency error is controlled within 0.1%. The total phase slip is about 5 degree.

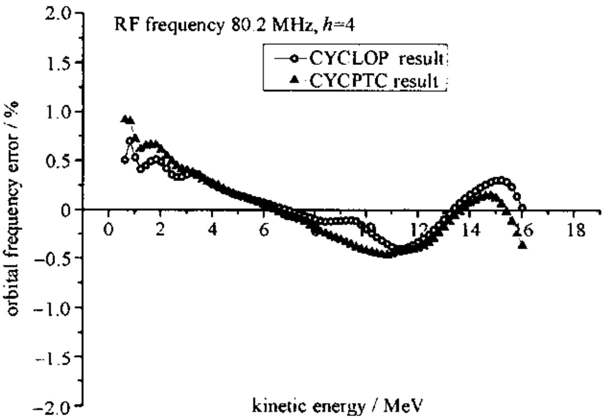

Fig. 7 Orbital frequency error at different energy, calculated by PTP and CYCLOP codes

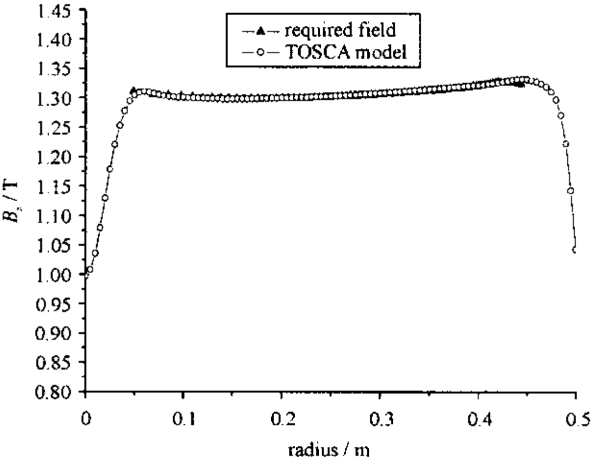

Fig. 6 Average magnetic field of the final optimized model

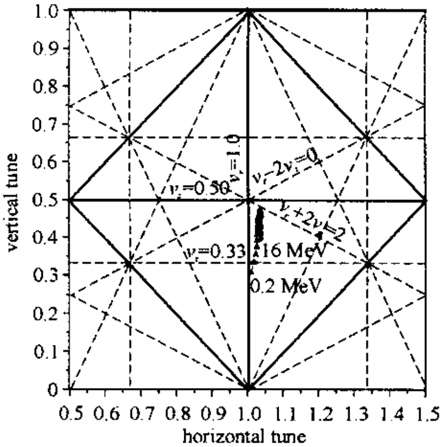

Fig. 8 Working diagram

Fig. 8 shows the tune diagram during acceleration. All resonance lines up to the thirds are drawn. It can be seen that both horizontal and vertical tunes are stable. Integer, half integer and Walkinshaw resonance crossing are avoided.

5 Conclusion

This paper described a systematic method for modeling and correction of the magnet of cyclotrons in the framework of CVPP. The method is validated by virtual magnet models and can be applied to the magnet measurement and shimming process during construction of cyclotrons. Currently, CVPP has been used for the design of cyclotrons in Huazhong University of Science and Technology. It is also applied as a validation tool for the magnet structure proposal in the 100 MeV high intensity cyclotron of CIAE (China Institute of Atomic Energy). In the near future, this platform is expected to exhibit power in the engineering construction and commissioning of compact cyclotrons.

Acknowledgement:

The authors would like to express appreciations to Prof. Zhang Tian-jue of CIAE for the Windows version CYCLOP code and fruitful discussions.

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基于虚拟样机的回旋加速器主磁铁设计与修正

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摘 要： 磁铁设计对于等时性回旋加速器极为关键。磁场分布需要满足粒子等时性加速和粒子径向、轴向聚集要求，同时避免危险的横向共振。提出了一种计算机辅助的自动化磁铁设计、建模和修正的方法，该方法在基于Python混合编程的虚拟样机集成设计环境中实现。详细描述了利用3维电磁场仿真软件TOSCA和自主开发的粒子束跟踪软件PTP对磁铁的优化过程，并给出了一个16 MeV负氢紧凑型回旋加速器的主磁铁设计实例。

关键词： 磁铁修正； 回旋加速器； 虚拟样机； Python语言