Article ID : 1001-4322(2003)06-0617-04

Beam centroid motion estimate for a high current LIA*

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Abstract : A high current linear induction accelerator now is being constructed in Institute of Fluid Physics. It consists of 18 blocks , totally 72 induction accelerating cells , and 18 connection cells with ports for beam diagnostic hardware and vacuum pump. The goal of the facility is to obtain high quality , high current pulse electron beams. In order to reduce corkscrew motion caused by energy spread and misalignment of a focusing system some measures to control the transverse motion of beam centroid must be taken. At first magnetic alignment is performed by using pulsed-wire technique very carefully , then the tilt errors is corrected by a pair of steering coils , which are located inside each cell , after that based on the alignment data a simple estimate of the beam centroid motion has been done by transfer matrix algorithm. In this paper , the calculated and analysis results are presented.

Key words : Corkscrew ; Beam centroid ; Transfer matrix

CLC number : TL501 **Document code :** A

1 Introduction

"Dragon Ⅰ" is a high current linear induction accelerator to produce high quality pulsed electron beams , which now is being constructed in Institute of Fluid Physics. The main body of the accelerator consists of 72 induction cells. Inside each cell there is a solenoid focus magnet and a pair of X , Y dipole steering magnets[1]. The cells are assembled in blocks of four followed by a resistance BPM and a connection cell with ports for beam diagnostic and vacuum pump. The electron beam source is a 3kA pulsed diode injector[2]. To transport and accelerate the pulsed electron beams to the end of the machine , corkscrew motion caused by energy spread and misalignment is concerned. In linear accelerators in which a solenoidal beam transport system is used , misalignment of the focusing system does exist , and there is still energy spread within the beam pulse duration.

During the block construction period , pulsed-taut wire technology was used to characterize the magnetic field of each cell and align the magnetic axis[3~5]. First of all , four accelerator cells and one connection cell are assembled on a mounting bench with the help of a laser track. The block mechanical axis is defined by the center of the beam pipe of the first and the last cells. Next the offset and the tilt of cell solenoid magnets are measured with taut wire and the tilt is canceled with steering magnets. After that the blocks are aligned and assembled to the body of accelerator very carefully with a laser track. The alignment status before correcting tilt by steering coils is shown in Fig 1 and Fig 2 . The maximum tilt along the beam line is 2 mrad and the

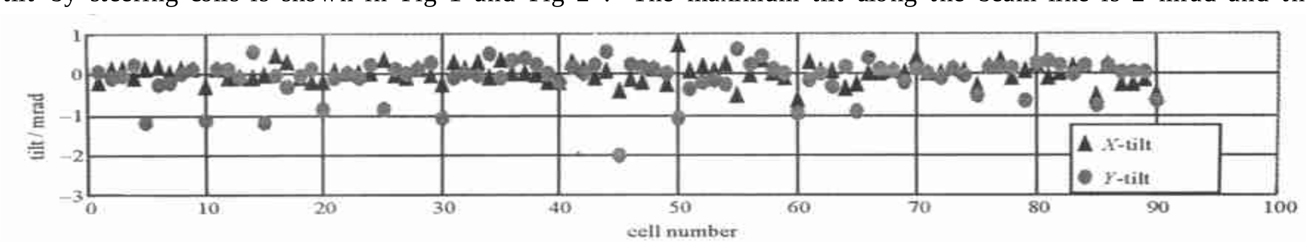

Fig. 1 Measured focus magnetic field tilt along the beam line

* **Received date :** 2003-02-25 ; **Revised date :** 2003-03-23
Foundation item : Sponsored by Fundamental Research Project of National Defence Science and Techuology
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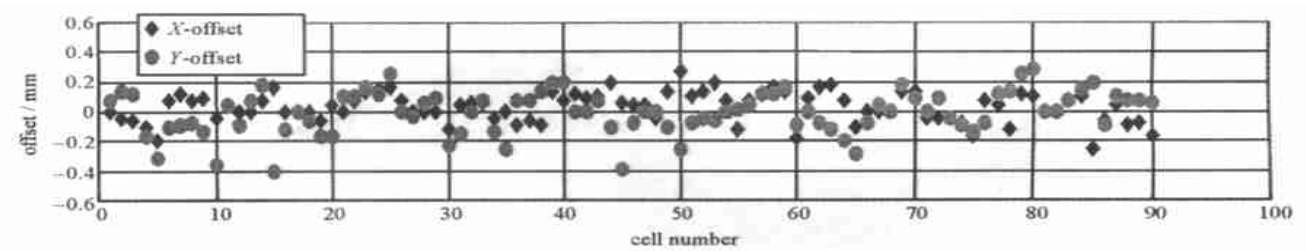


Fig. 2 Measured focus magnetic field offset along the beam line

maximum offset is 0.4mm.

In order to estimate the beam centroid motion of the pulsed beam under the circumstance of "Dragon I" transport magnetic system, a MATLAB program is written to calculate the centroid trajectory using matrix formalism.

2 Physical models

A simple model is used to trace the beam centroid motion. The input electron beam comes from a 60ns, 3kA, 3MeV injector; the diameter of the beam is around 5cm. It is transported through a beam line consisting of a serial of solenoids and is modeled as a string of rigid disks; we assume that there is no interaction between the beam disks. As a result all the beam disks can be transported together. We consider particle coordinates x, x', y and y', where x and y are the transverse spatial coordinates (in cm), $x' = \mathrm{d}x/\mathrm{d}z$ and $y' = \mathrm{d}y/\mathrm{d}z$ are the dimensionless transverse velocities, and the motion of the two coordinates is uncoupled.

During the calculation, we approximate the solenoid magnetic field as a series of small solenoids with hard edge and different amplitude, the width of each small solenoid is 2.8cm, the field amplitude is the average of the local magnetic field over the length of the small solenoid. Fig. 3 shows the approximation of the cell magnetic field distribution.

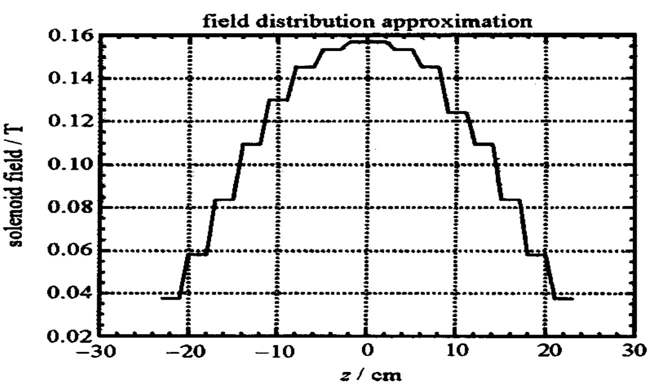


Fig. 3 Approximation of the magnetic field distribution

The accelerating gap is approximated only as an energy increment ΔE, in this way the beam enters each solenoid with different γ, and the magnetic field strength increases proportionally and simultaneously to the increase of energy.

To accommodate the misalignment of magnetic field axis, typically the offset and the tilt, special treatment equations are needed. Fortunately, the equations provided by LAMDA[6] are very suitable to solve the problem. The algorithm allow for a transverse displacement of the center of the solenoid δ_x, δ_y, a rotation about the axis of symmetry θ_r, and a small angle tilt about the center of the solenoid θ_t.

Mapping the beam centroid through the solenoid is accomplished in three steps: fringe field at entrance, uniform field and fringe field at exit. The matrixes used are as the following.

At the entrance of the solenoid:

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -k_c/2 & 0 \\ 0 & 0 & 1 & 0 \\ k_c/2 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{\text{in}} + \begin{bmatrix} 0 \\ -\frac{k_c}{2}\left(-\delta_y + \frac{L}{2}\theta_t \sin\theta_r\right) \\ 0 \\ \frac{k_c}{2}\left(-\delta_x + \frac{L}{2}\theta_t \cos\theta_r\right) \end{bmatrix}$$

The area with uniform field of the solenoid:

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{out} = \begin{bmatrix} 1 & \dfrac{\sin k_c L}{k_c} & 0 & \dfrac{-(1-\cos k_c L)}{k_c} \\ 0 & \cos k_c L & 0 & -\sin k_c L \\ 0 & \dfrac{(1-\cos k_c L)}{k_c} & 1 & \dfrac{\sin k_c L}{k_c} \\ 0 & \sin k_c L & 0 & \cos k_c L \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{in} + \Delta$$

At the exit of the solenoid:

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{out} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k_c/2 & 0 \\ 0 & 0 & 1 & 0 \\ -k_c/2 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_{in} + \begin{bmatrix} 0 \\ \dfrac{k_c}{2}\left(-\delta_y - \dfrac{L}{2}\theta_t \sin\theta_r\right) \\ 0 \\ -\dfrac{k_c}{2}\left(-\delta_x - \dfrac{L}{2}\theta_t \cos\theta_r\right) \end{bmatrix}$$

Where $k_c = KB_z/\gamma(\mathrm{cm}^{-1})$, $K = e/mc^2$, $L = 2.8\mathrm{cm}$ is the width of each small solenoid, B_z is magnetic flux density, $\gamma = (1-\beta^2)^{-1/2}$, and

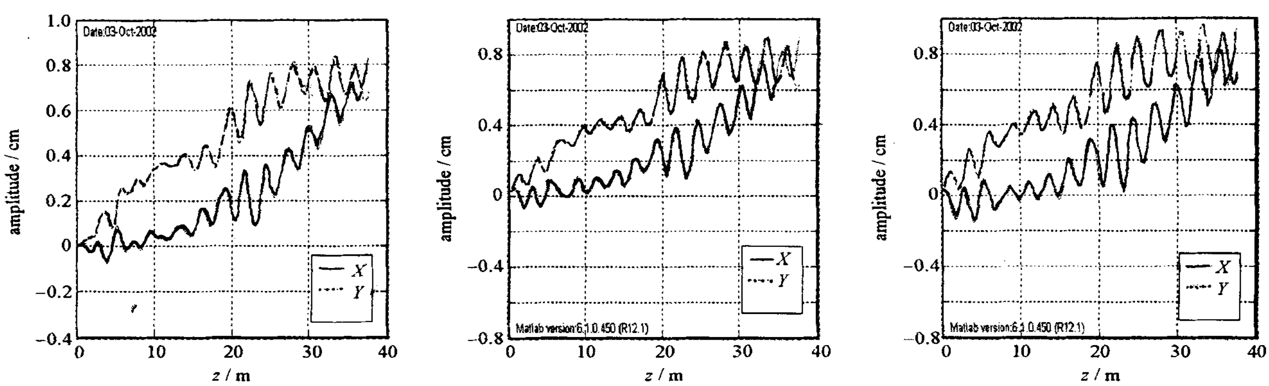
$$\Delta = \begin{bmatrix} \theta_t\left(L - \dfrac{\sin k_c L}{k_c}\right)\cos\theta_r + \theta_t \sin\theta_r + \theta_t \dfrac{(1-\cos k_c L)}{k_c}\sin\theta_r \\ \theta_t(1-\cos k_c L)\cos\theta_r + \theta_t \sin k_c L \sin\theta_r \\ \theta_t\left(L - \dfrac{\sin k_c L}{k_c}\right)\sin\theta_r - \theta_t \dfrac{(1-\cos k_c L)}{k_c}\cos\theta_r \\ \theta_t(1-\cos k_c L)\sin\theta_r - \theta_t \sin k_c L \cos\theta_r \end{bmatrix}$$

3 Cclculation and results

By varying the initial condition (x, x', y, y') of the particle at the entrance of the first cell of the accelerator, map the calculated results of each small solenoid; the output data of the previous small magnets is the input condition of the following small solenoid. According to the principle, one by one the beam centroid motion along the beam line of the accelerator is obtained.

Two cases are considered, one includes all magnetic field error (tilt and offset shown in Fig 1 and Fig 2). The other only considers the effect of the offset, because the tilt error can be canceled by the steering dipole magnets. The results of taut-wire magnetic axis alignment experiments show that in our case the tilt amplitude of all cells are reduced to less than 0.15mrad. Three groups of different initial parameters are considered: $x = 0$, $x' = 0$, $y = 0$, $y' = 0$; $x = 0$, $x' = 0.001$, $y = 0$, $y' = 0$ and $x = 0$, $x' = 0.001$, $y = 0$, $y' = 0.001$.

Fig. 4 and Fig. 5 show the calculation results when considering both the tilt and the offset error and only the offset error.



(a) $x = 0, x' = 0, y = 0, y' = 0$ (b) $x = 0, x' = 0.001, y = 0, y' = 0$ (c) $x = 0, x' = 0.001, y = 0, y' = 0.001$

Fig. 4 Claculated beam centroid trajectory (focus field with both offset and tilt error)

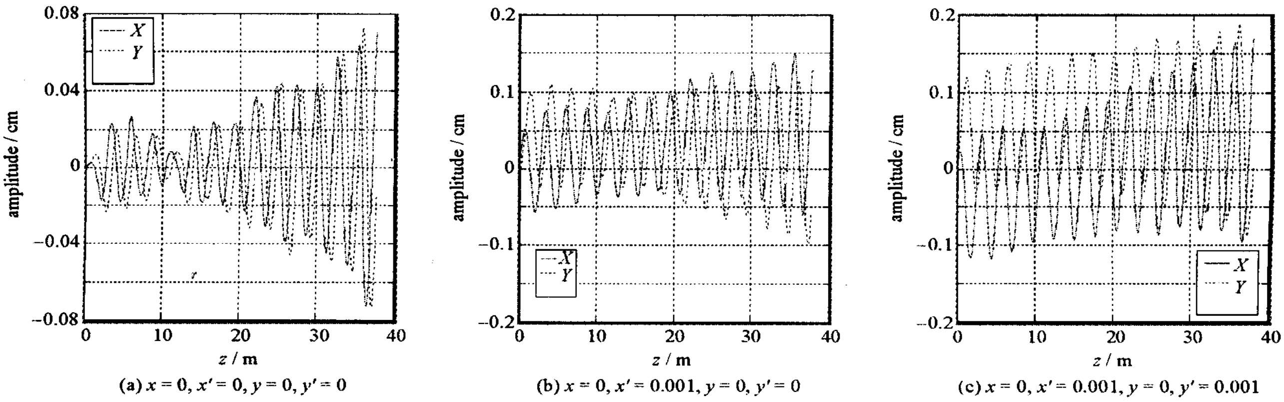


Fig. 5 Claculated beam centroid trajectory (focus field with offset error only)

From the three figures in Fig. 4 , with both the tilt and the offset error the displacement of beam centroid in x and y direction at the end of the accelerator is around 8mm. Changing the initial parameters x' and y' from 0 to 0.001 makes very small change on the trajectory. In this case the influence of magnetic field error is much stronger.

From the three figures in Fig. 5 the tilt error of all cell are canceled by steering dipole field, the beam centroid in x and y direction at the end of the accelerator is around 0.8mm when the initial beam parameter x' and y' equal to zero. Changing x' and y' to 0.001, the beam centroid displacement at the end of the accelerator increase to around 1.5mm.

4 Summary

The calculation results show if the input beam is of very good quality, the mainly error in "Dragon 1" focus magnetic field which will bring beam centroid displacement is the tilt error. By correcting the tilt error with steering dipole, the amplitude of the beam transverse motion will be reduced apparently. The calculation results also show that paying attention to the alignment of the focus magnetic field is needed, which also has been proved in beam transport experiments of "Dragon I".

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强流直线感应加速器中束流质心横向运动初步计算

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摘 要: "神龙一号"强流脉冲加速器由 72 个直线感应加速腔和 18 个用于测试和真空泵接口的多功能腔组成。直线感应加速器的研制建造中磁轴对中偏差和聚焦磁场的自然偏差所引起的束流质心偏移轨道中心是不可避免的,由于束脉冲期间存在能散,使束流产生 Corkscrew 运动,导致束流品质变坏。而束脉冲期间的能散只能减小到一定水平,因此必需采取一定的措施抑制 Corkscrew 幅度的增长。在加速器的安装阶段,脉冲悬丝技术被应用于准直加速段聚焦磁场,并在磁轴准直测试的同时对磁场固有倾斜偏差进行初步校正。根据脉冲悬丝测试所得实验数据,采用传输矩阵法对加速段束质心轨迹进行了初步估计,计算中考虑了各加速腔聚焦磁场的倾斜和偏移误差。给出了计算结果和分析。

关键词: 螺旋模; 束质心; 传输矩阵