Vol 15 No 6, June 2006
1009-1963/2006/15(06)/1226-05
Chinese Physics
© 2006 Chin. Phys. Soc.
and IOP Publishing Ltd

Control of beam halo-chaos by sample function*

Bai Long(白 龙)[a)†], Zhang Rong(张 荣)[a)], Weng Jia-Qiang(翁甲强)[b)],
Luo Xiao-Shu(罗晓曙)[b)], and Fang Jin-Qing(方锦清)[c)]

[a)] *College of Science, China University of Mining and Technology, Xuzhou* 221008, *China*
[b)] *College of Physics and Information Technology, Guangxi Normal University, Guilin* 541004, *China*
[c)] *China Institute of Atomic Energy, Beijing 102413, China*

(Received 10 July 2005; revised manuscript received 7 March 2006)

The K-V beam through an axisymmetric uniform-focusing channel is studied using the particle–core model. The beam halo-chaos is found, and a sample function controller is proposed based on mechanism of halo formation and strategy of controlling halo-chaos. We perform multiparticle simulation to control the halo by using the sample function controller. The numerical results show that our control method is effective. We also find that the radial ion density changes when the ion beam is in the channel: not only can the halo-chaos and its regeneration be eliminated by using the sample function control method, but also the density uniformity can be found at the beam's centre as long as an appropriate control method is chosen.

Keywords: beam halo-chaos, sample function, radial ion density, uniform-focusing channel
PACC: 0545, 4265

1. Introduction

In recent years, there has been growing interest in intense ion beams due to their attractive features in possible breakthrough applications, such as the production of nuclear materials, clean activity nuclear power systems, nuclear science, the production of radioactive isotopes for medical purpose.[1−18] However, the halo of an ion beam not only reduces the accelerator efficiency, but also damages the body and environment. If a beam is used, it is necessary to control the halo-chaos. At present, the ion beam through a periodic-focusing magnetic field or a uniform-focusing magnetic field is used widely. Study of controlling the beam halo-chaos propagating through a periodic-focusing channel has been carried out.[5,7,9−18] In this paper we investigate the halo-chaos of beam in a uniform-focusing magnetic field, and propose a sample function controller of strong nonlinearity and stability for controlling the halo. Since the halo-chaos is a spatio-temporal chaos which is sensitive and unstable, we find that the beam halo-chaos is controlled effectively by the sample function. Then we study the character of ion beam when the halo is not controlled or is controlled. The obtained results indicate that we can control not only the halo-chaos by applying some methods, but also the beam distribution in some sense.

2. Controlling the beam halo-chaos

2.1. Numerical method

At present, the particle-core model is used to investigate the beam halo-chaos widely. In this model, assuming the Kapchinsky–Vladimirsky (K-V) beam to be round and continuous, the dimensionless nonlinear equation of the beam envelope and the transverse equations of motion for a single ion in a uniform-focusing system are[2,3]

$$\frac{\mathrm{d}^2 r_\mathrm{b}}{\mathrm{d}s^2} + k_z(s) r_\mathrm{b} - \frac{K}{r_\mathrm{b}} - \frac{1}{r_\mathrm{b}^3} = 0\,, \tag{1}$$

and

$$\frac{\mathrm{d}^2 x}{\mathrm{d}s^2} + k_z(s) x + \frac{q}{\gamma_\mathrm{b}^3 \beta_\mathrm{b}^2 mc^2} \frac{\partial \Phi^\mathrm{s}(x,y,s)}{\partial x} = 0\,, \tag{2}$$

$$\frac{\mathrm{d}^2 y}{\mathrm{d}s^2} + k_z(s) y + \frac{q}{\gamma_\mathrm{b}^3 \beta_\mathrm{b}^2 mc^2} \frac{\partial \Phi^\mathrm{s}(x,y,s)}{\partial y} = 0\,, \tag{3}$$

*Project supported by the National Natural Science Foundation of China (Grant Nos 10247005 and 70071047) and the Scientific Research Foundation of China University of Mining and Technology for the Young (Grant No 2005A037).
†E-mail: bailong2100@163.com

respectively, where r_b is the beam radius and $s = vt$ is the axial coordinate, in which v is the axial velocity of the beam ions, K is a measure of the beam self-field, c is the speed of light; $\beta_b = v/c$, $\gamma_b = 1/\sqrt{1-\beta_b^2}$ is relativistic mass factor, q and m are the particle charge and rest mass, respectively; $\Phi^s(x,y,s)$ is the self-electric potential. $k_z(s)$ is constant, which characterizes the strength of the uniform-focusing field.

Because space-charges cause the nonlinear effects and energy exchange takes place between ions and the core, some ions can escape from the core and form a halo surrounding the core. We find the radial distribution of beam ions to be large and noncompact for the halo-chaos in the vicinity of the beam core as shown in Fig.3(a).

In the particle–core-interaction model, the self-field force acting on an ion is given by

$$F_r = -q\nabla\Phi^s(x,y,s)\,. \tag{4}$$

The nonlinear feedback control method is proposed based on the general strategy of controlling chaos in Ref.[5]. The approach is to apply a nonlinear feedback controller G to the right-hand side of Eq.(4), that is

$$F_r = -q\nabla\Phi^s(x,y,s) + G\,. \tag{5}$$

The force acting on an ion can be changed by controller G, at the same time the transverse velocity and energy of ions are reduced, so the tendency of ions escaping from the core is restrained. The loose ions in beam are compressed to the core field, and ions become concentrative after the halo-chaos is controlled, thus the goal of suppressing the halo-chaos is achieved.

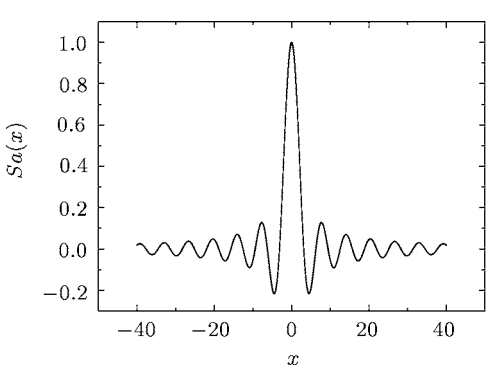


Fig.1. Sample function.

It is critical to select an effective controller G for controlling the halo-chaos, since the sample function has a strong stability, nonlinearity, and excellent localization property as shown in Fig.1, and it is utilized in the engineering. We put forward the sample function controller for controlling the halo using a sample function, namely

$$Sa(x) = \frac{\sin x}{x}\,. \tag{6}$$

The controller G is given as follows:

$$G = g[Sa(r_{rms}) - Sa(a_m)]\,, \tag{7}$$

where r_{rms} is the average root-mean-square radius, a_m is the match radius, g is the control coefficient. In our work, we apply a variational electric field $E(r_{rms})$ that is radical around a uniform-focusing channel, that is

$$E(r_{rms}) = \frac{g}{q}[Sa(r_{rms}) - Sa(a_m)]\,. \tag{8}$$

And the controller G is designed to be

$$G = Eq = g[Sa(r_{rms}) - Sa(r_{rms})] \tag{9}$$

for $r_{rms} - a_m \to 0$. Therefore the purpose of controlling the halo is achieved.

2.2. Numerical results

The particle-in-cell (PIC) simulation is used for studying the beam under a uniform- focusing channel. The main parameters used are as follows: the total number of ions is 5×10^4, the vacuum phase advance $\sigma_0 = 80^\circ$, tune-depression $\eta = 0.8$, $\eta = 1/a_m^2\sigma_0$ that characterizes the strength of space-charge effect. Mismatch factor $M = 1.5$, where the mismatch parameter gives the ratio of the initial beam radius to the matched radius, g is 8.5. The calculated parameters are as follows: matched radius $a_m = 0.9461747$ and perveance $K = 0.6283185$. The evolution periodic steps are 1800. The numerical simulation results are shown below.

The evolution of root-mean-square radius r_{rms} is smart and irregular before the halo is controlled as shown in Fig.2(a). However, in Fig.2(b), the evolution of r_{rms} is regular , and r_{rms} amplitude becomes so small that r_{rms} oscillation disappears after the halo is controlled.

Figure 3 shows the cross section of the beam before (a) and after controlling the halo-chaos (b). We find that the ion distribution in the beam is loose and nonuniform before the halo-chaos is suppressed, and the halo is visible as shown in Fig.3(a). After controlling the halo-chaos, not only the halo is removed, but also the radial ion density becomes uniform, at the same time we also find that the ratio of the cross section of the beam after controlling the halo-chaos to that before controlling it is 1/9.

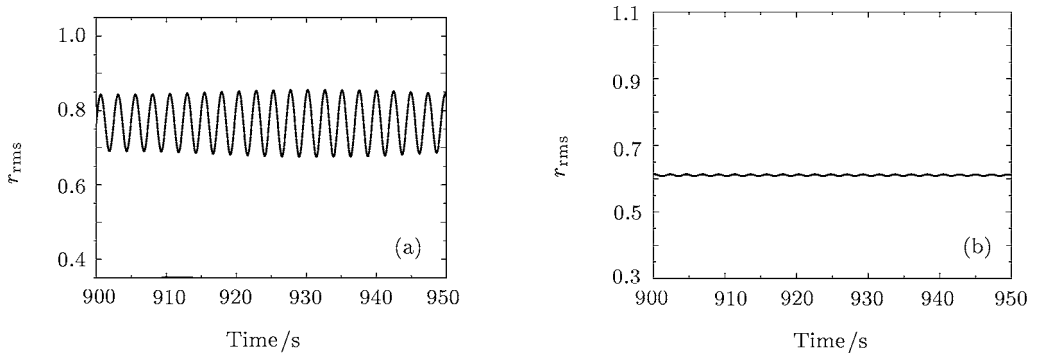


Fig.2. Evolution of average root-mean-square radius $r_{\rm rms}$ vs time (a) before and (b) after controlling the halo-chaos.

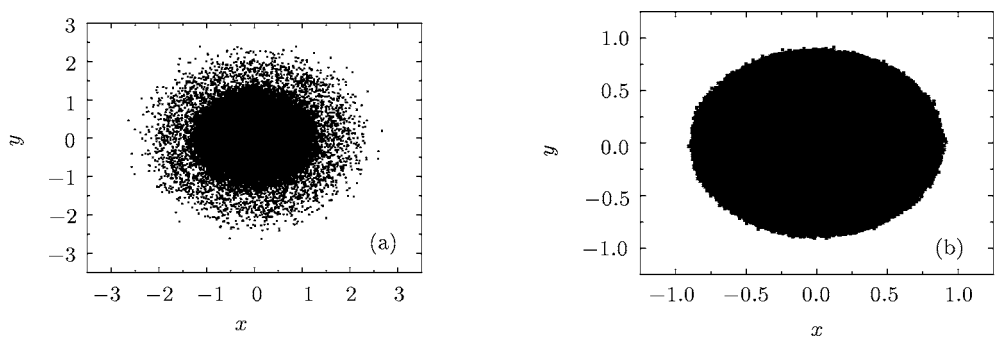


Fig.3. The ion distribution diagram in the (x, y) space at periodic section ($P = 600$) before (a) and after controlling the halo-chaos (b).

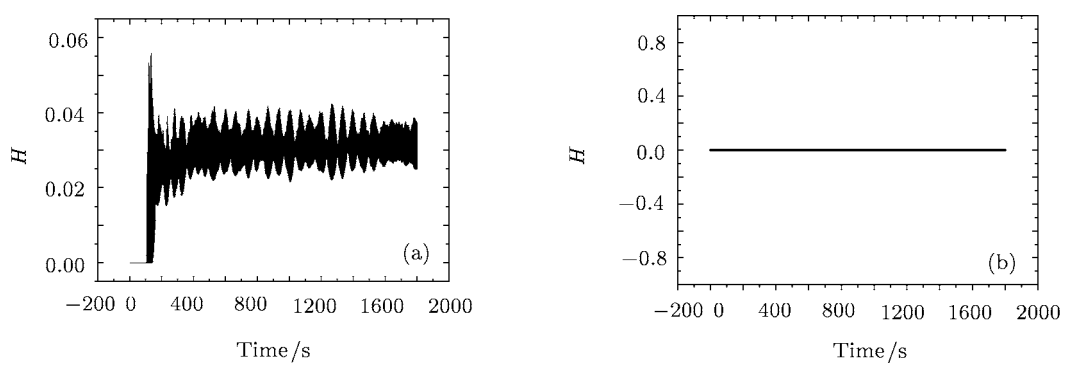


Fig.4. The halo-chaos strength factor H vs time before (a) and after controlling the halo (b).

In the simulation, we define the halo-chaos strength factor H as the ratio of number of ions at 1.75 $a_{\rm m}$ away from the centre to the total number of ions. H is a measure of the halo control. In Fig.4(a), we find that H is not zero, which implies that the halo is existent at all times before being controlled. with the halo controlled, H is zero, which means that the halo is removed by the sample the function controller.

3. Simulation of radial ion density in high-intensity ion beam

In Section 2, the halo-chaos is controlled by a sample function. We explore further the character of beam in the uniform-focusing system, where the beam parameters are set to be $\sigma_0 = 80°$, $\eta = 0.8$ and $M = 1.5$. 5×10^5 ions are used in our simulation. We still use the same controller as that in Section 2. By solving Eqs.(1)–(5) and (9), we explore not only the halo formation and its controlling, but also the radial ion density of beam. In this way, we can understand how the halo can be controlled better.

The initial distribution of the K-V beam is uniform as can be seen in Fig.5. When the beam

through a uniform-focusing channel is not controlled, the space-charge can cause the nonlinear effects and energy exchange between ions and the core, thus more and more ions may escape from the core, which causes the emittance growth and halo formation around the core as shown in Fig3.(a). Our simulation result indicates that the radial ion density in the beam varies radially, and two different density profiles are shown in Figs.6(a) and 6(b). The two curves are different, but compared with the initial distribution in Fig.5, the growth of ion radiation field occurs and radial ion density becomes nonuniform over the cross section of beam. We find that lots of ions accumulate in the centre, a few ions stay on the edge of the beam , the density curve is not of simple distribution, but has a maximum as shown in Fig.6(b). From the particle–core-interaction model, space-charge force is linear in the beam core, but nonlinear outside the core, and ions of mismatched beam are affected by the external magnetic field. The complexity of the force acting on ions results in such a shape of ion density curve.

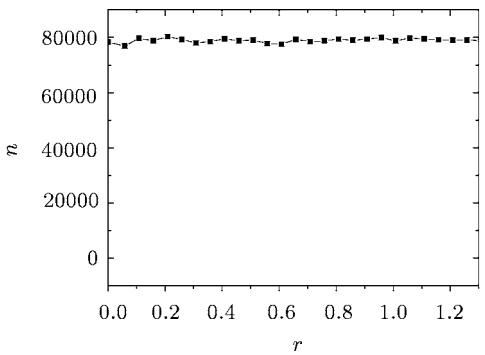


Fig.5. The initial density distribution of K-V beam.

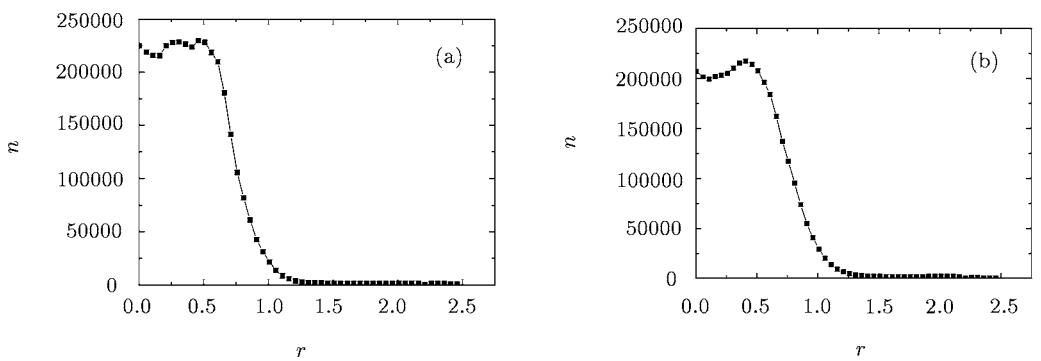


Fig.6. The ionic radial density before control. (a) $P = 600$; (b) $P = 1500$.

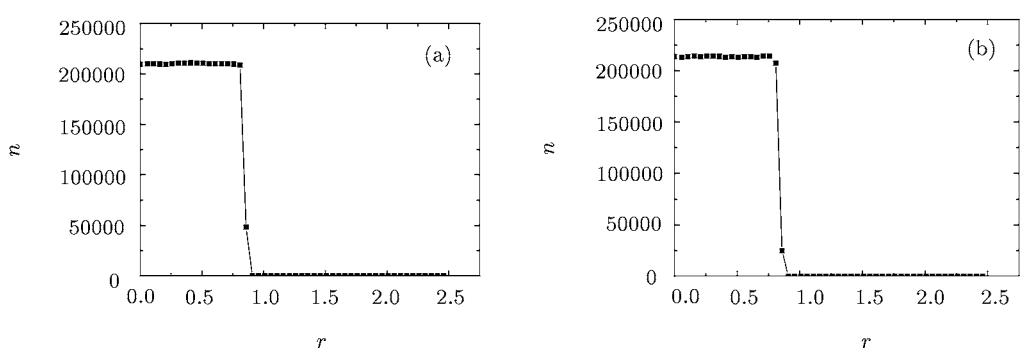


Fig.7. The radial ion density after controlling the halo. (a) $P = 600$; (b) $P = 1500$.

The beam halo-chaos is suppressed effectively by a sample function as shown in Fig.2(b), and the change in radial ion density occurs compared with the initial distribution, and the beam distribution before the halo is prevented. As a matter of fact, the purpose of controlling the beam distribution is achieved. The area of ions distribution becomes small, unlike that of the initial density distribution, the uniform density appears at beam's centre, and the density is more uniform than the initial density as shown in Figs.7(a) and 7(b). The lattice period is 1800 in our simulation, other density curves have identical features. The radial ion density after controlling the halo indicates that the ion density may be made to change some spatial distribution.

4. Summary

From the investigation of the effective control of beam halo-chaos and radial ion density, we can control not only the halo by chaos controlling method, but also the beam distribution as long as an appropriate control method is chosen, which may be a valuable try for the beam applications in the future.

References

[1] Fang J Q 2002 *Nature* **22** 63 (in Chinese)
[2] Chen C P and Davidson R C 1994 *Phys. Rev.* E **49** 5679
[3] Chen C P and Davidson R C 1994 *Phys. Rev. Lett.* **72** 2195
[4] Fang J Q and Yu X H 2004 *Chin. Phys. Lett.* **21** 1429
[5] Fang J Q, Chen G R, Zhou L L and Huang J J 2001 *Prog. Nature Sci.* **11** 113 (in Chinese)
[6] Gluckstern R L 1994 *Phys. Rev. Lett.* **73** 1247
[7] Fang J Q and Chen G R 2000 *High Power Laser and Particle Beams* **12** 647 (in Chinese)
[8] Wang T-S F 2000 *Phys. Rev.* E **61** 855
[9] Gao Y, Weng J Q, Fang J Q and Luo X S 2001 *Acta Phys. Sin.* **50** 1440 (in Chinese)
[10] Zhu L W, Weng J Q, Gao Y and Fang J Q 2002 *Acta Phys. Sin.* **51** 1483 (in Chinese)
[11] Fang J Q, Gao Y, Weng J Q, Luo X S and Chen G R 2001*Acta Phys. Sin.* **50** 435 (in Chinese)
[12] Gao Y, Luo X S and Weng J Q 2004 *Acta Phys. Sin.* **53** 4131 (in Chinese)
[13] Huang G X, Luo X S and Fang J Q 2004 *High Power Laser and Particle Beams* **16** 1191 (in Chinese)
[14] Liao G H, Weng J Q, Cheng L C and Fang J Q 2005 *Acta Phys. Sin.* **54** 35 (in Chinese)
[15] Fang J Q, Yu X H and Chen G R 2003 *Chin. Phys. Lett.* **20** 2110
[16] Bai L, Weng J Q, Fang J Q, and Luo X S 2004 *Acta Phys. Sin.* **53** 4126 (in Chinese)
[17] Bai L, Weng J Q and Fang J Q, 2005 *Chin. Phys. Lett.* **22** 2180
[18] Fang J Q, Wang Z S and Chen G R 2004 *Commun. Theor. Phys.* **42** 557 (in Chinese)