Beam-loss driven injection optimization for CSNS/RCS

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Abstract This paper summarizes the painting injection optimization for the Chinese Spallation Neutron Source (CSNS) ring. This optimization focuses on two main design goals: the lower beam loss and a space-charge tune shift low enough to avoid strong resonances. Finally, the 3-D particle tracking is performed and we get some important results about the beam properties and beam loss.

Key words painting injection, beam loss, space charge effect

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1 Introduction

The Chinese Spallation Neutron Source consists of a 1.6 GeV rapid cycling synchrotron (RCS) and a 80 MeV linac, which is to be upgraded to 130 MeV in the second stage. The accelerator provides high intensity, high energy proton beams for various scientific fields. The 1.6 GeV RCS is designed to accelerate the 1.88×10^{13} protons per pulse at a 25 Hz repetition rate in the first stage of 80 MeV injection.

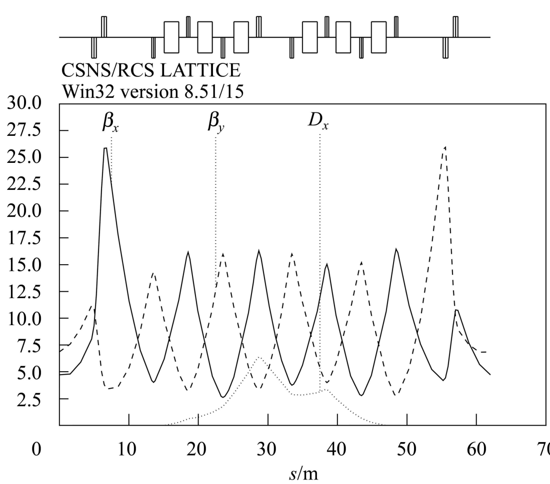

Fig. 1. Twiss functions of CSNS/RCS.

The present lattice of the CSNS/RCS is a hybrid structure, consisting of FODO cells in the arcs and doublet cells in the straight sections [1]. There are four long straight sections in the lattice and every straight section is divided into three available drifts (6.5, 9.3 and 6.5 m long, respectively). The twiss functions along one of the four superperiods are shown in Fig. 1.

To achieve hands-on maintenance, we place collimators at some positions around the ring to remove the beam halos and tails. Ideally, these locations become the only “hot spots” of the machine where special handling is required. Even if the beam is lost in the collimators, we consider it a controlled beam loss. As a convention, the uncontrolled beam loss should be kept below 1W per meter [2]. To guarantee hands-on maintenance, two methods should be implemented:

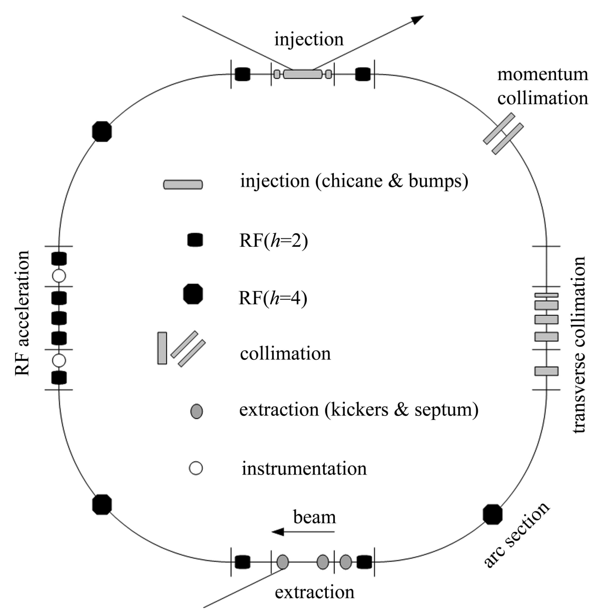

Fig. 2. Schematic layout of the RCS ring.

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optimizing the design for lower beam loss and localizing nearly all the beam loss in the collimation system.

Figure 2 shows a schematic layout of the RCS ring. Injection, extraction and RF cavities occupy a 9.3 m long straight section respectively. The transverse collimation system is constrained in one of the long straight sections and the momentum collimator is placed at the peak of dispersion.

2 Injection

In CSNS/RCS, the beam loss can be roughly divided into two ways: 1) longitudinal beam loss, occurs when particles are outside the RF bucket or reach a momentum deviation larger than the momentum acceptance of the machine; 2) transverse beam loss, occurs when particles exceed the collimator's acceptance, such a beam loss is induced mainly by the space charge effect.

In order to decrease the longitudinal beam loss, the longitudinal injection scenario with 50% chopping rate is adopted [3]. What's more, the RF program and momentum offset are optimized to improve the bunching factor [3]. The main parameters of the injection beam are shown in Table 1.

Table 1. Beam parameters of the injection.

parameters	values
injection energy	80 MeV
chopping rate	50%
phase advance	from $-\pi/2$ to $\pi/2$
injection turns	200
RMS momentum spread	1‰
RMS emittance	1 πmm·mrad
momentum offset	2.5‰
injection RF volts	23 kV

The injecting beam emittance of the 80 MeV linac is 1 πmm·mrad in rms and the acceptance of the 1.6 GeV RCS is 360 πmm·mrad limited by the primary collimator. Although with a large ring acceptance, the nonlinear part of the space charge force will lead to non-uniformity of the beam distribution, thus a large beam loss will probably happen. In order to reduce the beam losses that are critical in high power accelerators, painting into the large acceptance with good uniformity is usually required. One parameter indicating the influence of the space charge effects is the tune shift. In the case of uniform distribution, the tune shift due to space charge effects can be expressed by:

$$\Delta Q = -\frac{r_{\rm p} N}{2\pi\varepsilon\beta^2\gamma^3 B_{\rm f}}, \qquad (1)$$

where $r_{\rm p} = 1.53\times10^{-18}$ m is for the classical proton radius, N for the accumulated particles, ε for the un-normalized emittance, $B_{\rm f}$ for the longitudinal bunching factor, β and γ are for the Lorentz factors.

The distribution of particles in phase space can be controlled by changing the injection point. However a change of the injection point is not realistic, because the position of stripping foil cannot be changed easily at high speed. Actually, changing the injection points for phase space painting is available by changing the position of the closed orbit or injection angle. In the case of CSNS/RCS, we adopt the former.

The basic painting schemes include correlated painting and anti-correlated painting. With the correlated painting scheme, the beam fills both the horizontal and vertical acceptance ellipses from inner to outer and the final distribution in the real space x-y will be almost rectangular. With the anti-correlated painting scheme, the beam fills the horizontal acceptance ellipse from inner to outer and the vertical

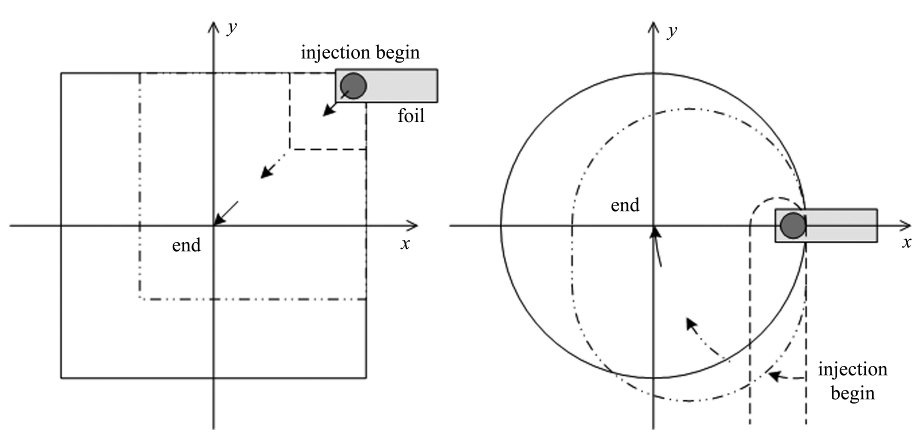

Fig. 3. Basic painting schemes, the left is the x-y correlated painting, the right is the x-y anti-correlated painting.

acceptance ellipse from outer to inner and the final distribution in the real space x-y will be elliptical. In CSNS/RCS, the beam is injected into the ring at a dispersion-free region, the beam phase space painting in the transverse direction is conveniently de-coupled from the longitudinal beam dynamics. Furthermore, painting in the horizontal and vertical direction can be adjusted independently. The injection system is designed to accommodate both the x-y correlated and the x-y anti-correlated painting schemes, illustrated in Fig. 3.

From the point of view of depressing the space charge effect, the most favorable distribution in the transverse direction is a uniform one. To achieve a uniform distribution in phase space, the orbit shift equation is given as [4],

$$x, y = a\sqrt{t/T} \quad \text{for correlated painting,} \tag{2}$$

$$x = a\sqrt{t/T} \text{ and } y = a\sqrt{1-t/T} \quad \text{for anti-correlated painting.} \tag{3}$$

where x and y are the shift in the closed orbit from the injection point, a is the radius of the beam and T is the time of injection period. Table 2 shows the results of two painting schemes. In either of the two cases the orbit shift is given as Eqs. (2) and (3), and the painting emittance is 200 πmm·mrad.

Table 2. Results of different painting schemes.

	correlated	anti-correlated
average foil hits	2.36	3.39
$\varepsilon_{\rm RMS}$/(πmm·mrad)	47/45	66/46
$\varepsilon_{50\%}$/(πmm·mrad)	89/83	130/73
$\varepsilon_{95\%}$/(πmm·mrad)	208/199	257/235
$\varepsilon_{99\%}$/(πmm·mrad)	249/242	295/286
beam loss during injection course	9%	0.86%

The correlated painting scheme has the advantage of pulling the painted distribution away from the stripping foil in both directions, resulting in less foil traversals. What's more, the emittances in both horizontal and vertical directions are fairly uniform. Unfortunately the beam loss of correlated painting is intolerable. To illustrate this phenomenon, please refer to Fig. 4. It's a schematic view of the beam, collimator and vacuum pipe in the real space. Nearly all the apertures in CSNS/RCS are circular or elliptical, thus the rectangular particle distribution formed by correlated painting will result in great beam loss.

Now we use the ratio of different number particles' emittance to judge the uniformity of particle distribution. To a completely uniform anti-correlated painting, the ratio of emittance is $\varepsilon_{\rm RMS}$: $\varepsilon_{50\%}$: $\varepsilon_{95\%}$: $\varepsilon_{99\%}$ = 1 : 2 : 3.8 : 3.96; to a Gaussian distribution, the ratio is $\varepsilon_{\rm RMS}$: $\varepsilon_{50\%}$: $\varepsilon_{95\%}$: $\varepsilon_{99\%}$ = 1 : 1.39 : 6 : 9.2. In a real proton accelerator, the result of painting is strongly influenced by the space charge effect.

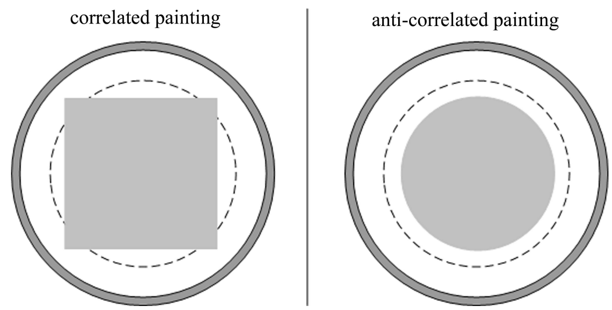

Fig. 4. Schematic view of the beam, collimator and pipe in real space.

Despite having less beam loss during the injection course, the anti-correlated painting scheme results in nonuniform particle distribution in the vertical direction. What is shown in Fig. 5 is the particle distribution at the end of the anti-correlated painting injection. In the figure we can see that the vertical distribution is closer to Gaussian one more than uniform one. Such a distribution causes larger center density and greater tune shift, and this will lead to more beam losses in the following acceleration course.

In fact, Eqs. (2) and (3) are applicable in case of removing the space charge effect. In the high current proton synchrotron, the influence of space charge effect on particle distribution cannot be ignored. In the CSNS/RCS anti-correlated painting scheme, we choose to inject a large vertical and small horizontal emittance at the outset. This means that particles with large vertical emittance spend more time in the beam during injection, compared with the correlated case in which painting proceeds from the smallest to the largest emittance in both directions. This is the main reason for a worse particle distribution in the vertical direction.

To reduce the center density of anti-correlated painting, we can adopt the hollow anti-correlated painting scheme. Figs. 6 and 7 show the particle distribution maps at the end of the hollow anti-correlated painting, without and with space charge effect. Comparing these two figures, we can easily find that the space charge forces spread and fill the hollow part dramatically. This is precisely what we prefer.

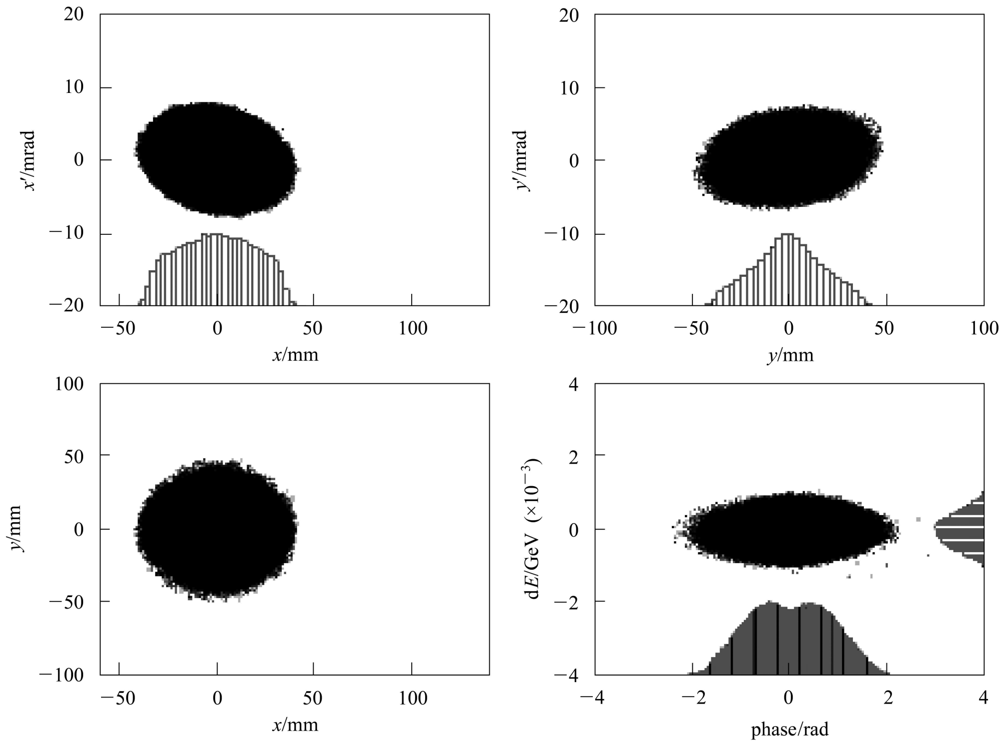

Fig. 5. Particle distribution at the end of anti-correlated painting injection.

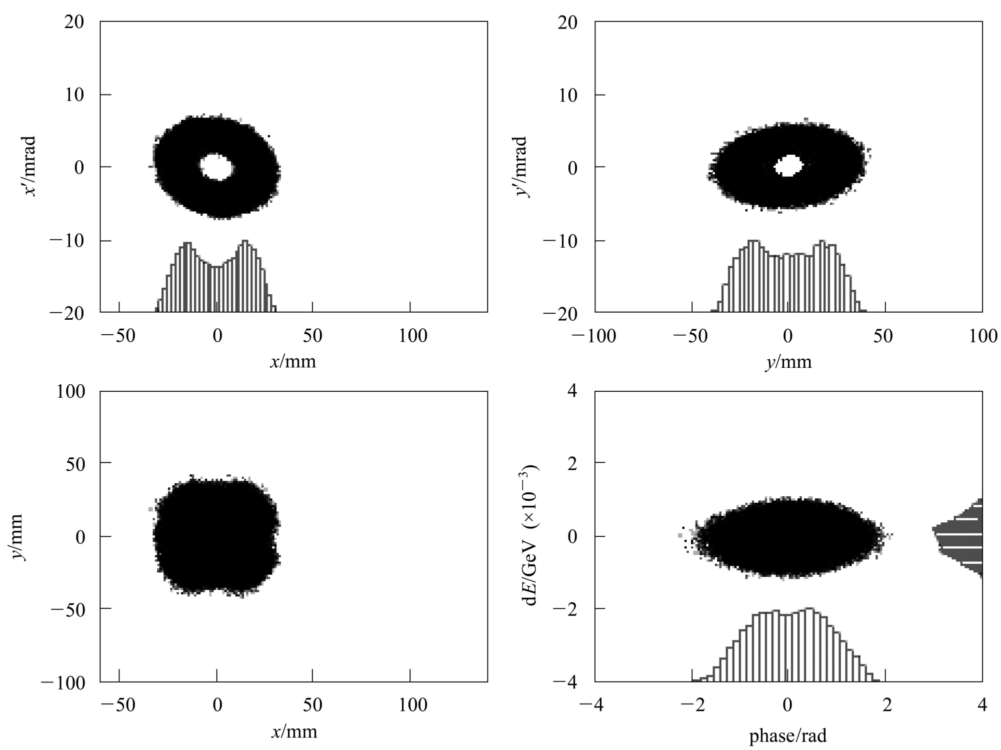

Fig. 6. Particle distribution at the end of the hollow anti-correlated painting injection (without space charge effect).

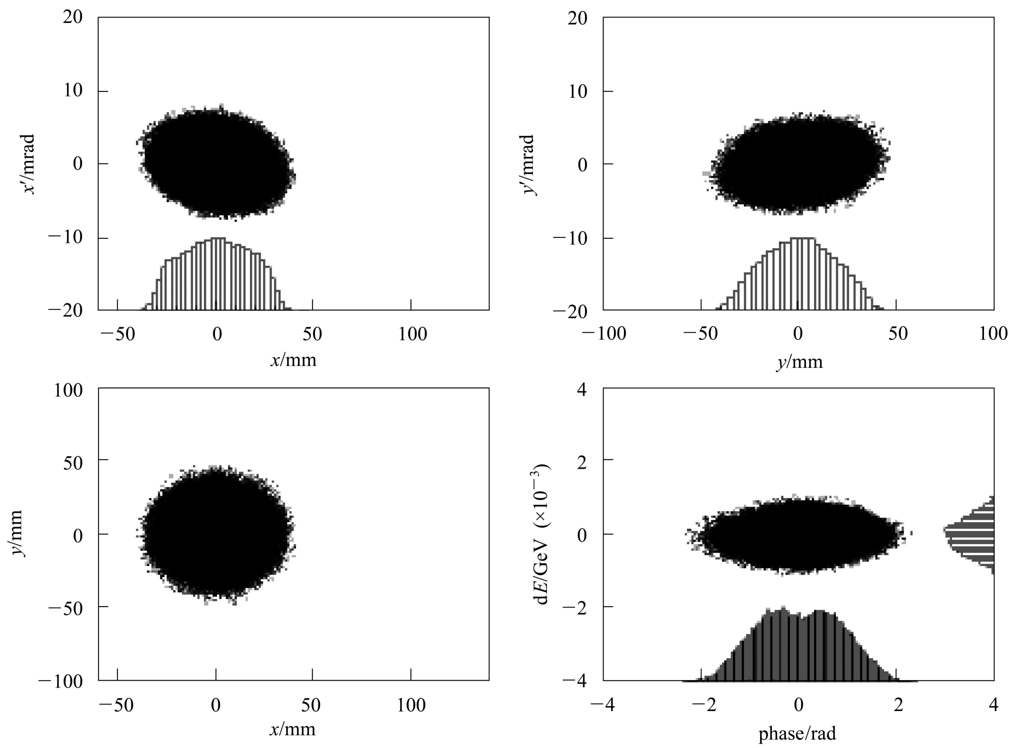

Fig. 7. Particle distribution at the end of hollow anti-correlated painting injection (with space charge effect).

Table 3 shows the result of the hollow anti-correlated painting scheme. The emittances in both horizontal and vertical directions are fairly uniform. Furthermore, the beam loss is the least. The only weakness is that there are more foil traversals, but it is still under control. So the hollow anti-correlated painting scheme is the best one at present.

Table 3. Results of the hollow anti-correlated painting scheme.

average foil hits	4.05
$\varepsilon_{\mathrm{RMS}}$/(πmm·mrad)	53/46
$\varepsilon_{50\%}$/(πmm·mrad)	104/82
$\varepsilon_{95\%}$/(πmm·mrad)	225/212
$\varepsilon_{99\%}$/(πmm·mrad)	268/267
beam loss during injection course	0.63%

3 3-D particle tracking simulation

Till now, we have carried out various design optimizations for less uncontrolled beam loss, including: linear dynamic, RF volts program, aperture, injection, beam collimation [5], etc. We have performed multi-particle tracking simulation including what is mentioned above with the code ORBIT [6] developed by SNS. And we can estimate the beam loss more precisely.

We perform end to end simulation from injection to extraction. The numbers of macro particles are 400000 and the meshes are 128×128×128 which have been proved to be reasonable. The result is shown in Fig. 8. The total beam loss rate is 4.1%, of which 94% is lost during the first two seconds.

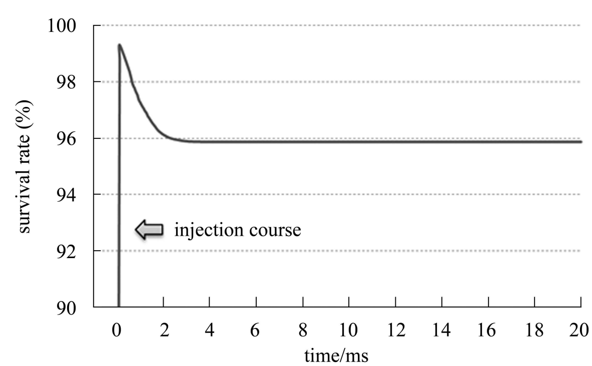

Fig. 8. Beam survival rate changing with time.

In addition, the collimation efficiency of the ring is 96.5%. In other words, most lost particles are concentrated in the collimators, and the uncontrolled beam loss rate is only 0.14%. This indicates the collimation system's effect is significant. The uncontrolled beam loss distribution in the ring is shown as Fig. 9, from which we can see that the design can satisfy the requirement of 1 W/m energy deposit except two quadrupoles. We can resolve this matter through increasing the local aperture or adding local shielding.

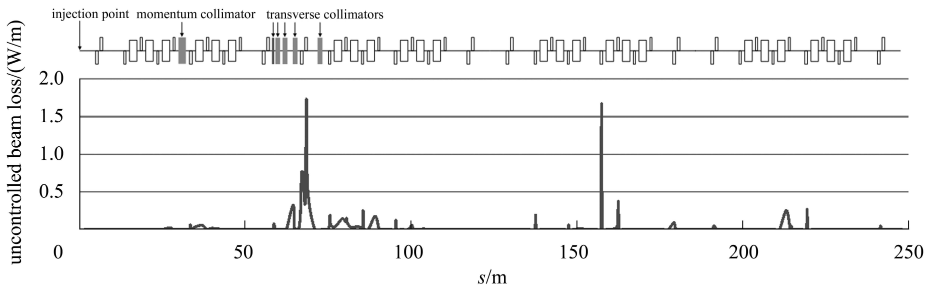

Fig. 9. The uncontrolled beam loss along the ring.

4 Summary and discussion

The hollow anti-correlated painting scheme is effective to reduce the beam loss and decrease the tune shift. It's a good choice for CSNS/RCS. But painting injection is important not only for reducing the beam loss caused by space charge effect but also for controlling the transverse beam profile on the neutron target. However, it is not easy to control the beam profile at the extraction at RCS because of the acceleration process. The transverse emittances of beam at different moments are shown in Fig. 10.

During the acceleration process, the beam distribution trends to Gaussian distribution which is what we don't want. The relation between the painting injection and extraction beam distribution is still under study.

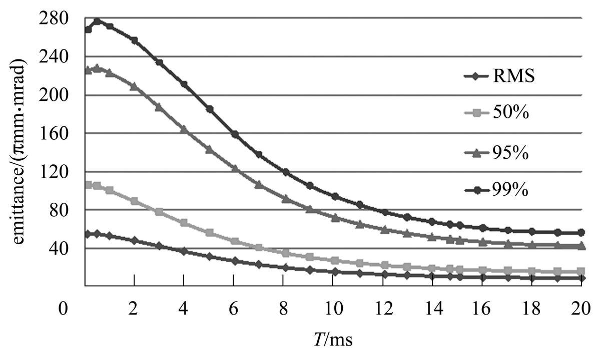

Fig. 10. Evolution of the vertical emittance during acceleration.

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