Space-charge and resonance considerations for choosing the SNS ring working points

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Space-charge and resonance considerations for choosing the SNS ring working points

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I. INTRODUCTION

The beam power of the SNS is an order of magnitude higher than that of existing accelerator facilities. This imposes a strict requirement on the uncontrolled beam loss at a 10^{-4} level. The major source of beam loss is associated with machine resonances. Thus, the first step towards reaching low beam loss is to find the best suitable working points on the tune diagram.

In this note, we explore the tune space by considering machine resonances and the effect of space charge, which can drive particles into these excited resonances. In addition, space charge itself can induce resonances. Our present studies were driven by these facts and by the fact that previous working points [1] were identified for the shorter ring with 220 m circumference. Also, the combined effects of space charge and magnet errors raised concern for the nominal working point [2], [3].

II. TUNE SPACE

The tunability of the new 248 m circumference lattice has been extensively explored [4]. It was shown that we are limited by the conditions of achromatic arcs, which are required for dispersion-free staright sections, and optical matching, to avoid significant beatings of the beta functions, to **one unit** in the horizontal tune $\mathbf{Q_x = [6, 7]}$ and to approximately **three units** in the vertical tune $\mathbf{Q_y = [4, 7]}$. As a result, we limit our present studies to this tune space.

We first consider only the structure resonances. Figure 1 indicates the most dangerous resonance lines: the 2nd order resonances are shown in red, green represents the 3rd order structure resonances, and blue denotes 4th order structure sum resonances. One can see that **we are limited** to a tune space **below the half − integer** in the horizontal direction. We previously observed that working points with very close tunes lead to undesirable space-charge coupling resonances. For this reason we adopted a split tune base working point $(Q_x, Q_y) = (6.3, 5.8)$ [1]. This particular working point choice, although good from the standpoint of space-charge effects alone, has potential problems when magnet errors and imperfection resonances are considered. For this working point, the major problem arose from exciting the skew-quadrupole sum resonance $(Q_x + Q_y = 12)$ [2], [3]. This resonance line is clearly shown in red in Fig. 1. Additional problems with this working point surfaced when we included the effect of the quadrupole fringe fields. As a result, we observed a significant beam loss due to the combined effect of the space charge and fringe fields [5].

A close look at Fig. 1 indicates that we have three triangles which are free from structure resonances. Unfortunately, one of them is located at 2 units split between the vertical and horizontal tunes, which would lead to matching problems. We thus concentrate on the remaining triangles without significant tune split ($\mathbf{(Q_x, Q_y) = [6, 6.5]}$ space). However, we should have at least some split of tunes in order to avoid significant space-charge coupling.

We now proceed by including non-structure resonances up to the 4th order. The tune space for $\mathbf{(Q_x, Q_y) = [6, 7]}$ is shown in Fig. 2, with black lines indicating the non-structure resonances. Fig. 2 also shows the expected tune spread of a 2MW beam, where the green tune footprint corresponds to the tune spread due to space charge alone, the red tune footprint includes an additional effect of momentum spread with $\Delta p/p = 0.6\%$, and the pink tune footprint shows the combined effect of the space charge and $\Delta p/p = 1\%$.

- Choosing the working point similar to the one shown in Fig. 2 would give us significant margin for intensity upgrade, and could allow us to paint to a smaller emittance (if only structure resonances need to be avoided). However, the beam will cross major 3rd order resonances. These resonances are not structural but can lead to significant losses if the excited terms are strong or the storage time is sufficiently long. In the SNS case, the injection time is only 1 msec, and the driving terms for these resonances are expected to be relatively small. We thus do not expect significant beam losses during 1 msec injection period for this type of working point. To explore this question quantitatively, we performed some preliminary numerical simulations which we present in the next section.

• Another option is to stay below the 3rd order resonance lines, which still gives us significant room for the tune spread (**0.33**). In fact, we would like to stay even below the 4th order resonance line which will be excited by the quadrupole fringe fields, an important limitation for the SNS. This would significantly limit our tune spread space to only **0.25** in each direction. Therefore, we would anticipate significant losses in high-intensity operation. For low beam intensities, such as those expected during the commissioning period, such a working point could be desirable because of the absence of dangerous resonances. Such a working point is described in the next section. Similar arguments for choosing the best working point were recently presented by G. Parzen [6].

• Finally, we retain the option of a split-tune working point (up to one unit, for example, $(Q_x, Q_y) = (6.23, 5.24)$), but do not consider this option in this note.

A. Working points with 3rd order resonance crossing

We now choose a working point (**type one**) which would allow us to have significant intensity upgrade, for example, $(Q_x, Q_y) = (6.4, 6.3)$, and explore the effect of crossing 3rd order resonances. Figure 3 shows the half-unit tune space for this working point together with the tune spread for a 2MW beam with $\Delta p/p \approx 0.6\%$. The major 3rd order resonances intersecting the tune distribution are normal sextupole $3Q_x = 19$ and skew-sextupole $2Q_x + Q_y = 19$. We explore these resonances by using the SNS package of the

UAL [3]. First, we intentionally introduce large systematic sextupole errors in the dipoles to drive the third order resonances and to force a significant beam loss during the short time beam accumulation time of 1 msec. Figure 4 shows the effect of the systematic sextupole component with $b_3 = 500$ units (normalized to 10^{-4} of the main field at the reference radius), and the combined effect of both the normal and skew components with $b_3, a_3 \approx 500$ units. As expected, we observe both resonances and associated beam losses. For example, Fig. 5 shows the resonance excited by $b_3 = 500$ units.

Next we introduce an additional source of sextupole errors by including chromatic sextupoles with the strength necessary to drive the chromaticity to zero. The combined effects of such sextupoles and various errors is shown in Fig. 6. Note that we again used relatively large magnetic field sextupole components in order to produce significant beam halo. In real magnets it is expected that the multipole errors will be much smaller, of the order of a few 10^{-4} units. Our simulation results with more reasonable (smaller) errors are shown in Fig. 7, where we included systematic and random errors in magnet fields, fringe fields of quadrupoles, x, y misalignments and tilt of the magnets. In the simulations used for Fig. 7 the important sextupole component source due to the dipole fringe fields was not included. For this reason we included slightly higher sextupole components of $b_3, a_3 = 5 \cdot 10^{-4}$ than are actually expected. Our future studies will include the dipole fringe fields as well as realistic values of multipole errors based on magnet measurements.

To achieve losses at 10^{-4} level we require 10^{-3} losses at the primary scraper, which could be located in the acceptance region of $[240, 280]$ π mm mrad. Figure 7 indicates that we have much larger halo in this region. However, the beam halo increase is not dramatic compared to the space-charge only case without magnet errors shown by the blue color. Thus, we can proceed in a way similar to our optimization for the nominal working point (paint to a smaller beam emittance and optimize painting bump function) to minimize beam halo to 10^{-3} level in the acceptance region of $[240, 280]$ π mm mrad.

B. Working points which avoid dangerous resonances

Another type (**type two**) of working point is one which avoids the dangerous 3rd order resonances. Here, we discuss a working point which avoids both dangerous 3rd and 4th order resonances. We can always increase the tunes of a working point slightly, if only the 3rd order resonances are a concern. As an example, we choose $(Q_x, Q_y) = (6.23, 6.2)$. Unfortunately, this point is quite close to the space-charge coupling resonance $2Q_x - 2Q_y = 0.06$, but otherwise our tune distribution will cross only the difference 3rd and 4th order resonances. Thus, if the space-charge coupling does not create problems (This issue will be addressed by our future studies. The main question here is to determine whether the space-charge coupling will allow us to satisfy the target requirements.) we should expect significant losses only for the high-intensity operation when the integer resonance lines are encountered. For example, the tune spread of a 2MW beam is shown in Fig. 8. For commissioning intensities much smaller than $2 \cdot 10^{14}$ we do not cross half-integer resonances, and we then have the flexibility to use larger tune split to avoid space-charge coupling. As a result, working points of this type are good candidates for the initial commissioning stage. We should also note that a working point similar to this is successfully used at PSR (although, with one unit split between the integer tunes), but that at the highest intensities beam broadening is observed when a significant number of particles cross the half-integer resonances [10].

Usually, gradient errors are assumed to limit the intensity of the beam. This limit (incoherent space-charge tune shift) is based on the assumption of constant beam size. However, the beam size depends on the oscillation amplitudes of the individual particles, and if the gradient error causes these amplitudes to grow, the beam size also grows. Thus an approach of restricting the incoherent space-charge tune shift not to cross half-integer betatron line is not self-consistent and is too conservative. The correct theory [7] (see also [8]) indicates that one should use the "effective" [9] tune shift rather than the incoherent tune shift when looking at resonance conditions for low order betatron resonances. This theory is in good agreement with experimental studies at PSR [10]. It indicates that the space-charge limit is less restrictive, and that the choice of a working point close to the half-integer $(6.23, 6.2)$ may be satisfactory even for high-intensity SNS operation with a 2MW beam.

III. SUMMARY

In this note, we explored the tune space and identified several regions with suitable working points. Systematic study of these working points as well as inclusion of all realistic effects is currently in progress [11].

In **type one** regions we can have significant margin for intensity upgrade and also can have sufficient tune split to avoid space-charge coupling. But we encounter several imperfection resonances, including the 3rd order. Preliminary studies do not show dramatic losses due to resonances in this region. However, more detailed studies are necessary, and are currently in progress. In addition, this region could be used to explore the possibility and efficiency of various correction schemes.

Another region (**type two**) avoids dangerous resonances but may be limited with respect to intensity, and does not allow a significant tune split to avoid space-charge coupling. Working points in this region could be suitable candidates for the commissioning stage.

IV. ACKNOWLEDGMENTS

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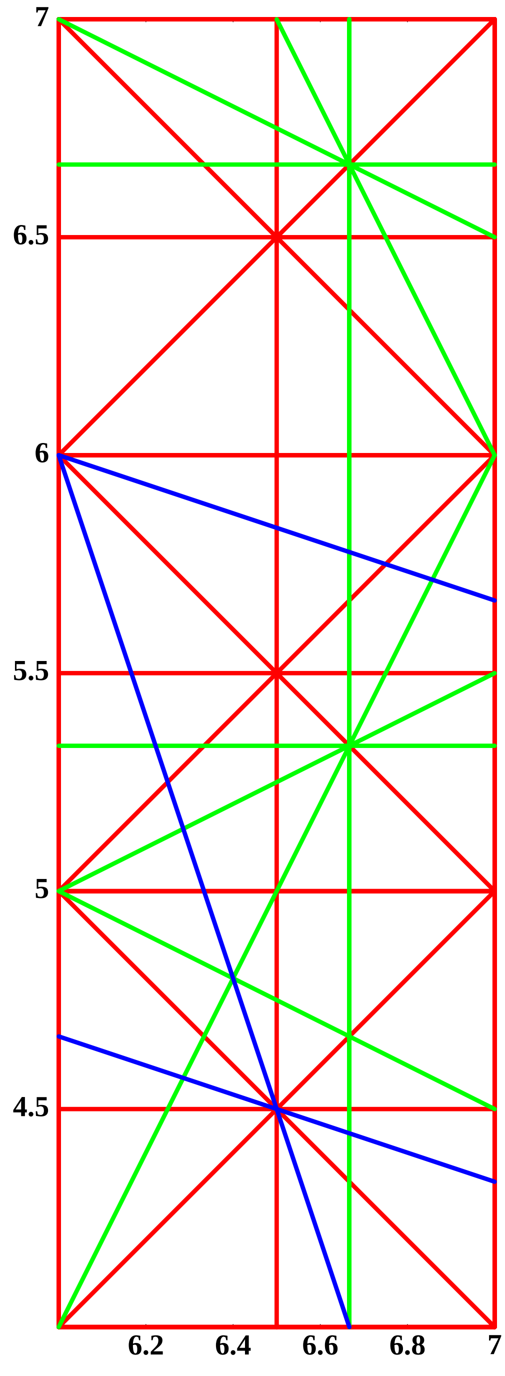

FIG. 1. Tune space for 248 m lattice of the SNS with acceptable optical mismatch; a) red color shows 2nd order resonances b) green color shows 3rd order structure resonances c) blue color shows only sum structure resonances of 4th order.

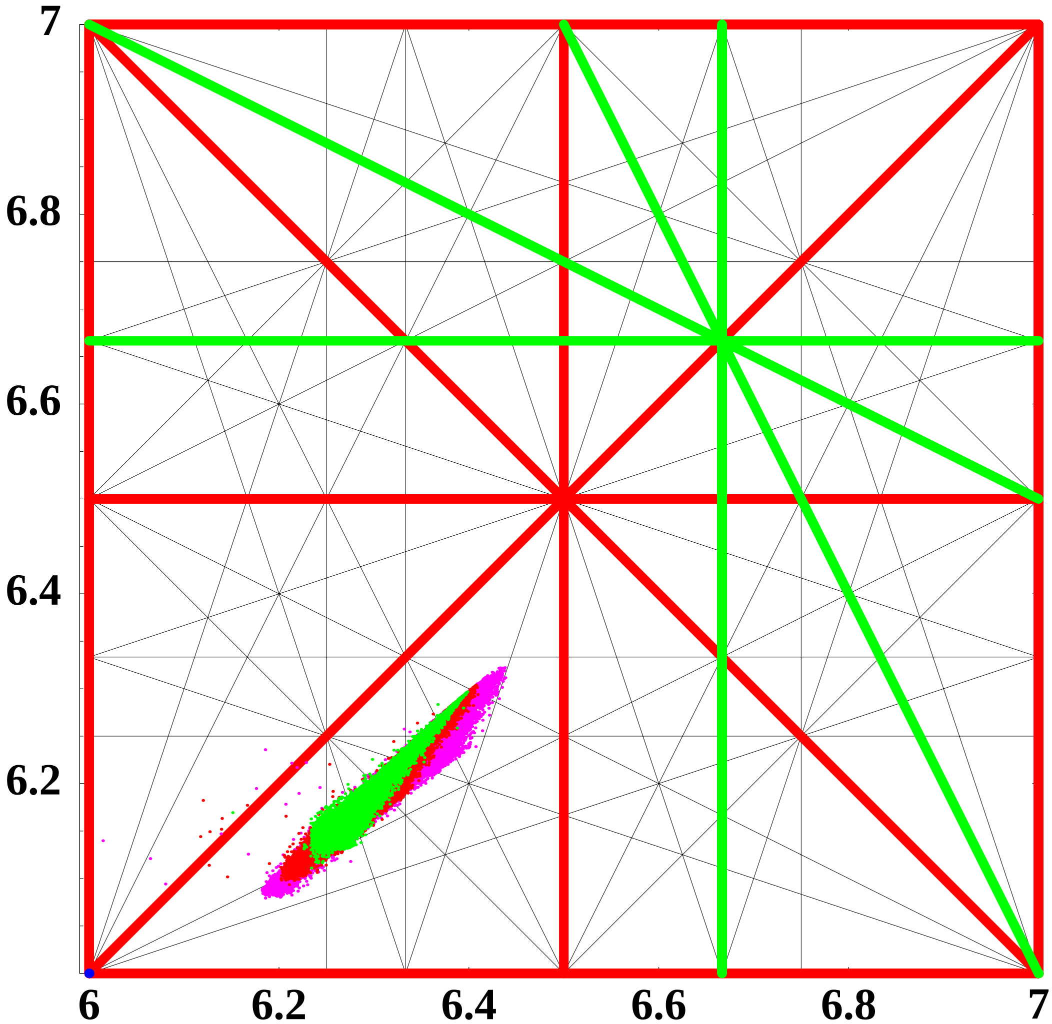

FIG. 2. Working point $(Q_x, Q_y) = (6.4, 6.3)$ with tune spread for a 2MW beam; a) green color represents the tune spread due to the space charge alone b) red color also includes momentum spread of $\Delta p/p = 0.6\%$ c) pink color shows the combined effect of the space charge and $\Delta p/p = 1\%$.

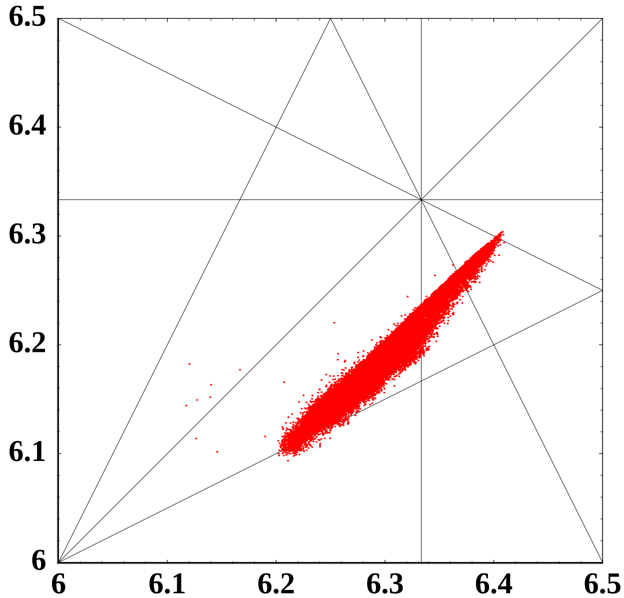

FIG. 3. $Q_x - Q_y$ tune space diagram. An example of a working point $(Q_x, Q_y) = (6.4, 6.3)$ (**type one**) with tune spread for a 2MW beam (space charge and $\Delta p/p = 0.6\%$). Only the 3rd order resonance lines are shown.

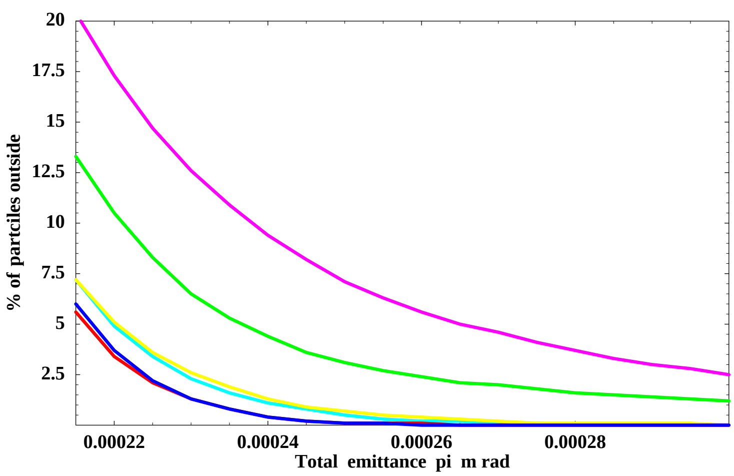

FIG. 4. Excitation of 3rd order resonances by large systematic component of sextupole errors; a) blue color shows beam halo due to the space charge alone b) red color also includes some magnet field errors of 10^{-4} level c) light blue and yellow color show an additional effect of systematic sextupole component with $b_3 = 50$ and $b_3, a_3 = 50$ units (normalized to 10^{-4} of the main field at the reference radius), respectively d) green line shows beam blow-up due to $b_3 = 500$ units e) pink color shows beam blow-up due to combined effect of $b_3, a_3 = 500$ units.

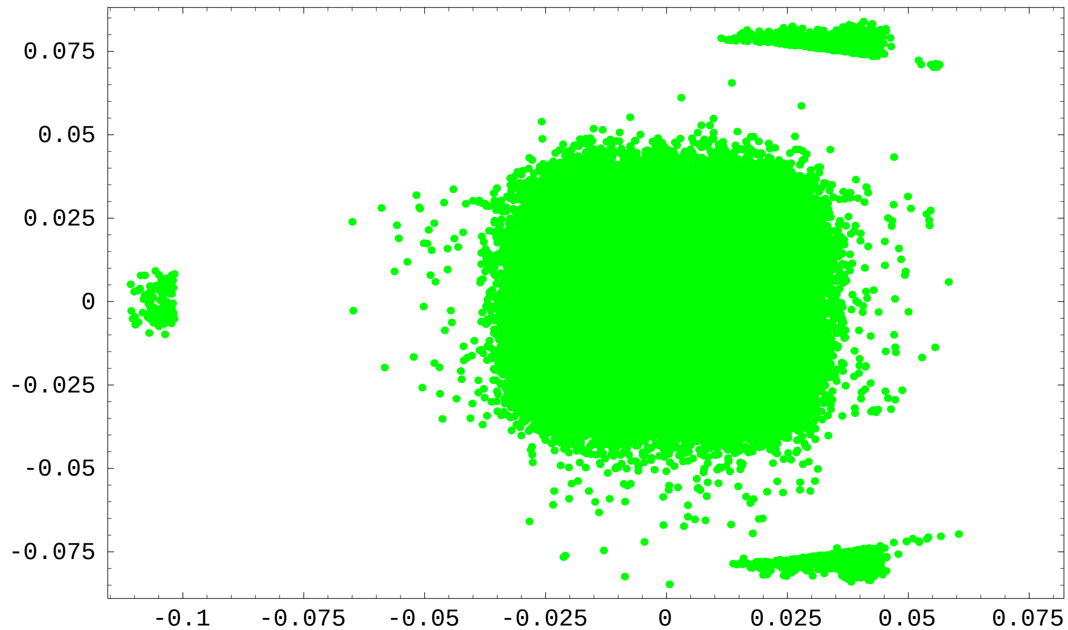

FIG. 5. $X - Y$ phase space in meters. Excitation of 3rd order resonance by large systematic errors with $b_3 = 500$ units.

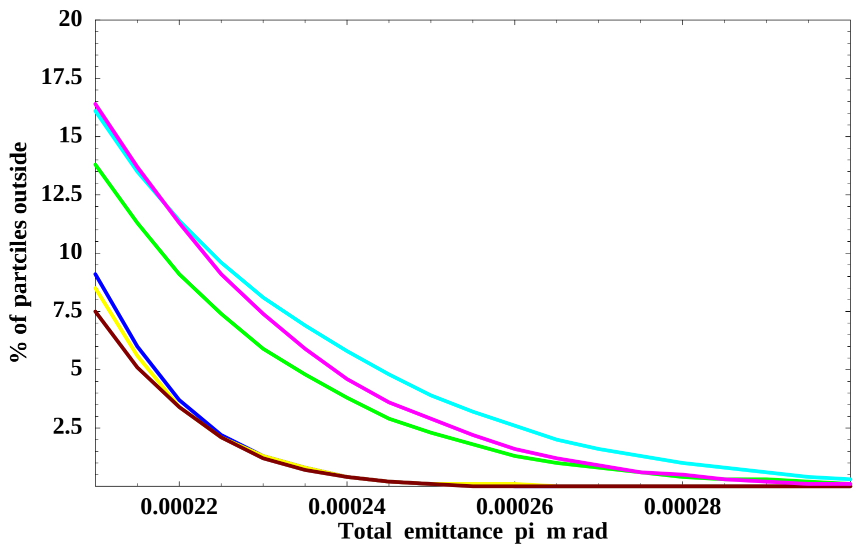

FIG. 6. The upper three curves in this figure show the effect of the chromatic sextupoles in combination with various types of errors; a) light blue color shows beam halo due to the systematic component of $b_3 = 50$ and chromatic sextupoles in the absence of misalingments b) pink color shows the effect of $b_3 = 50$, chromatic sextupoles and quadrupole fringe fields c) green color shows the effect of $b_3 = 50$, chromatic sextupoles and x, y misalignments of 0.5 mm.

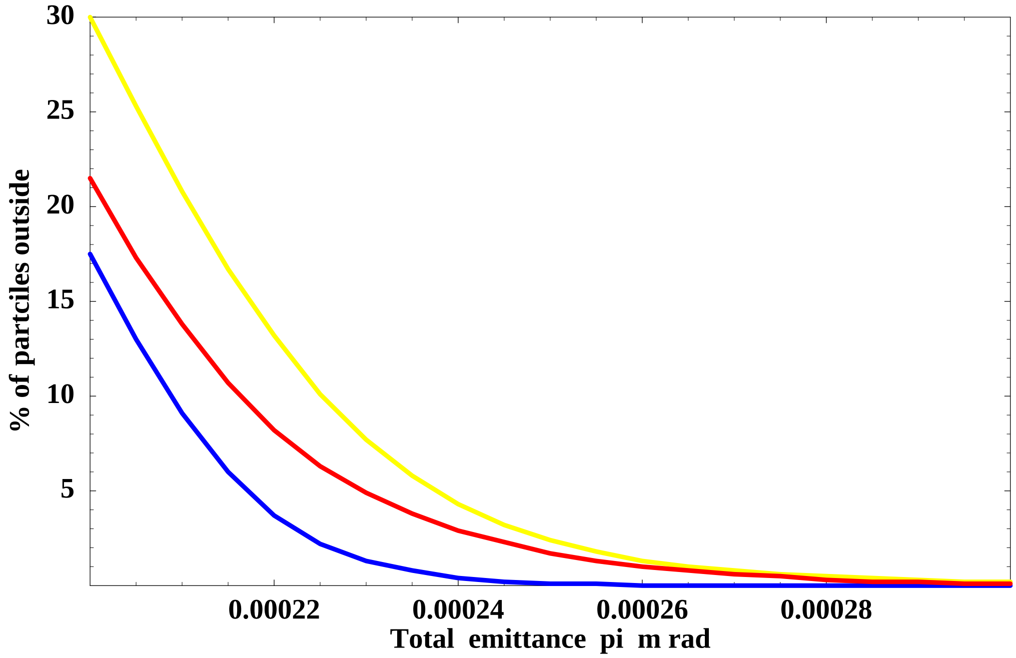

FIG. 7. Beam halo due to expected errors; a) blue color shows halo due the space charge alone b) red color corresponds to the case of both systematic and random magnet field errors at a few units at 10^{-4} level, chromatic sextupoles and quadrupole fringe fields c) yellow color shows an additional effect of x, y misalingments of 0.5 mm and magnet tilt of 1 mrad.

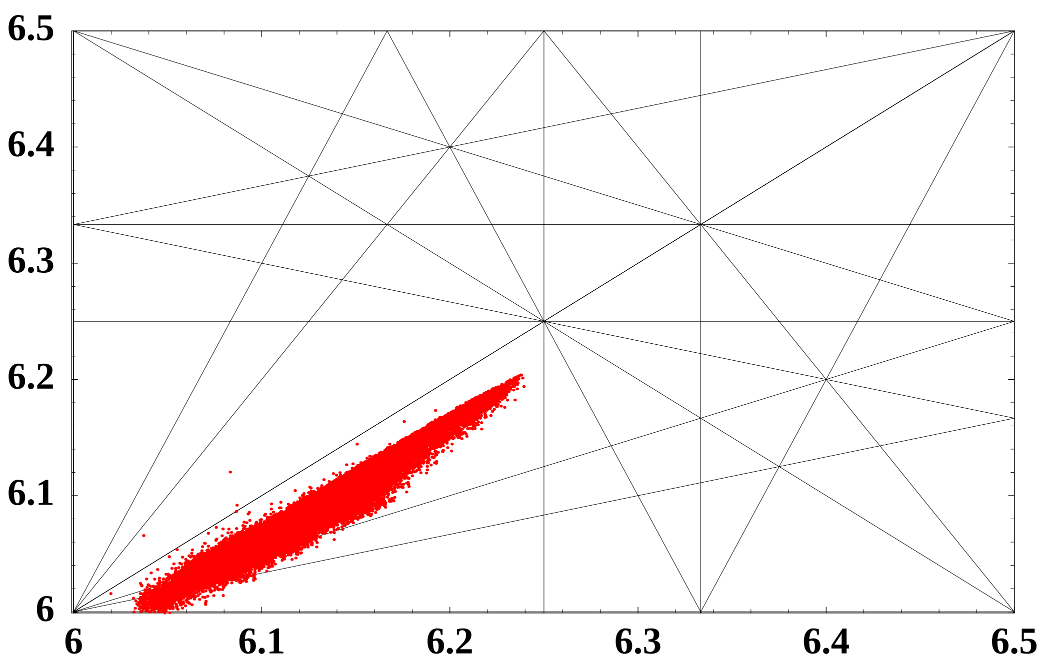

FIG. 8. An example of **type two** working point $(Q_x, Q_y) = (6.23, 6.2)$. Tune spread (red) of a 2MW beam due to the combined effect of the space-charge and $\Delta p/p = 0.6\%$.