ON LIOUVILLIAN HIGH POWER BEAM ACCUMULATION

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Abstract

It is acknowledged that the injection of high power proton beams into synchrotrons must be done using stripping injection of H^- beams which are accelerated by an injector, as done in many facilities worldwide such as ISIS, JPARC, SNS and CERN. However, this technique is not necessarily the only way of accumulation and in some cases might not represent the best choice. For example in the case of the ESSνSB Accumulator Ring, injecting the protons into the ring could represent savings in capital cost, reduced risk of losses in the linac and transfer lines and simplification to the overall project. This work presents the development of a method allowing to optimize the 4D Liouvillian accumulation of high-power proton and heavy ion beams.

INTRODUCTION

The European Spallation Source (ESS), presently under construction in Lund, Sweden, will be the world's brightest neutron source, powered by a 5 MW proton linac. The ESS linac can, with moderate modifications, be used for the production of a very intense neutrino beam. This word studies the possibility to inject protons from the linac directly into the accumulator using a 4D Liouvillian multi-turn accumulation process.

- added complexity of the dual source front-end;
- issues with H- source reliability and lifetime;
- losses due to H- stripping in the linac and transfer line to the ring
- substantial increase in complexity of the control and safety system.

THE METHOD

100% Emittance

LIO is built to optimize the injection parameters considering that 99.999% of the injected beam should be stored without loss (50 W loss budget). To avoid the need for particle tracking and heavy simulations at this exploratory phase, the calculations are then done considering un-normalized transverse emittance of $\varepsilon_{100} = 26\varepsilon_{rms} = 2.8$ mm mrad in both planes. One can notice that this emittance is defined by the far halo particles for which the space charge effects from the beam core are very weak.

Optimized injection Parameters

The link between the injected (index i) and stored (index r) beam parameters to obtain an optimized 4D injection is given by the equations below

$$\frac{\beta_{r,i}}{\alpha_{r,i}} = \frac{\beta_{i,x}}{\alpha_{i,x}} = \frac{x_i}{x'_i} = -\frac{x_i - x_{co}(n)}{x'_i - x'_{co}(n)} \quad (1)$$

$$\frac{\beta_r}{\beta_i} = \left(\frac{\varepsilon_r}{\varepsilon_i}\right)^{1/3} \quad (2)$$

with similar equations also valid for the vertical plane. α and β are the Courant-Snyder (C-S) parameters, ε the emittances, (x_i, x'_i) the injected beam position and angle in the closed-orbit coordinate system, $(x_{co}(n), x'_{co}(n))$ he closed-orbit position and angle at turn n.

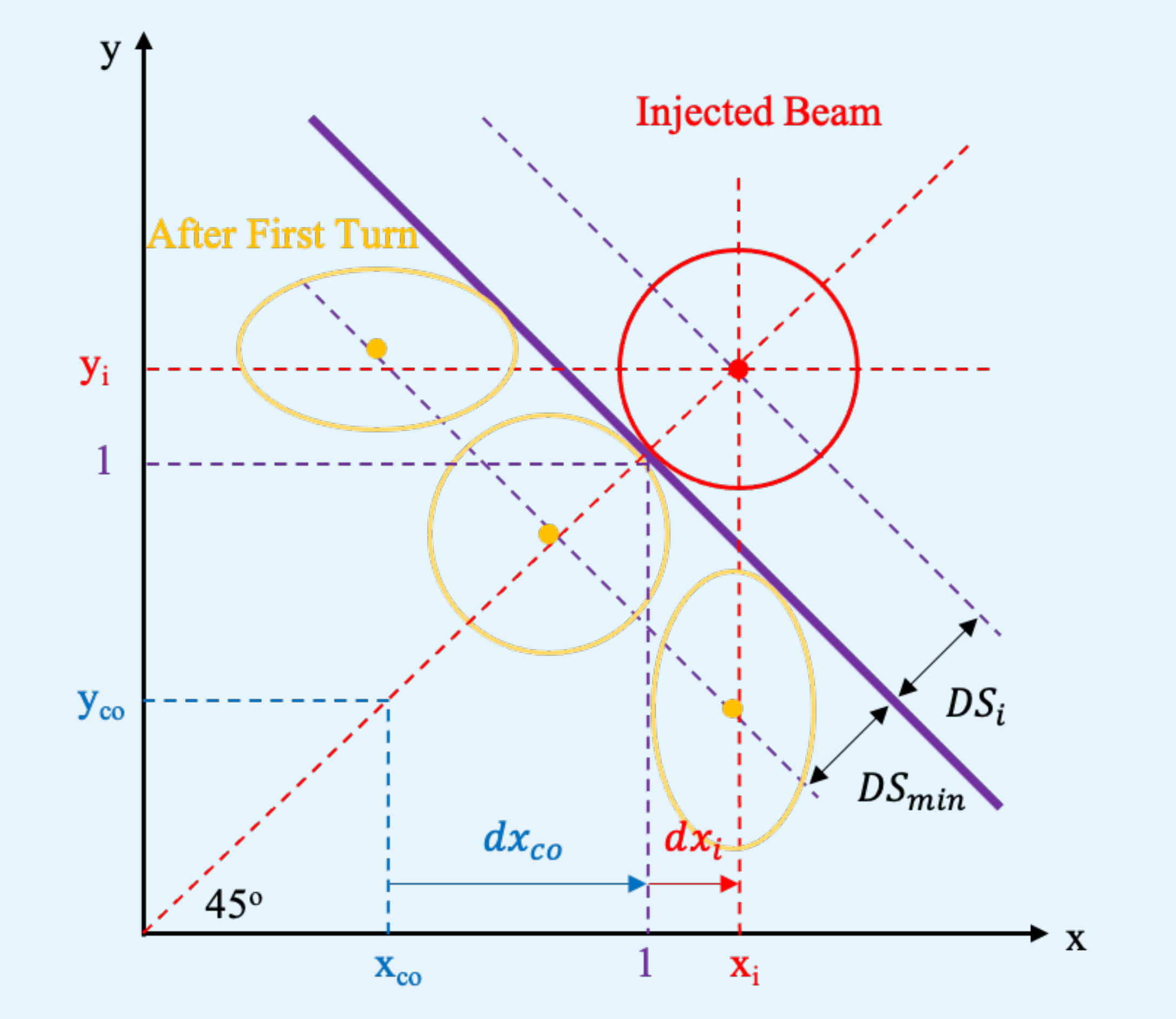


Figure 1: Geometry and parameter definitions for the injected and stored beams.

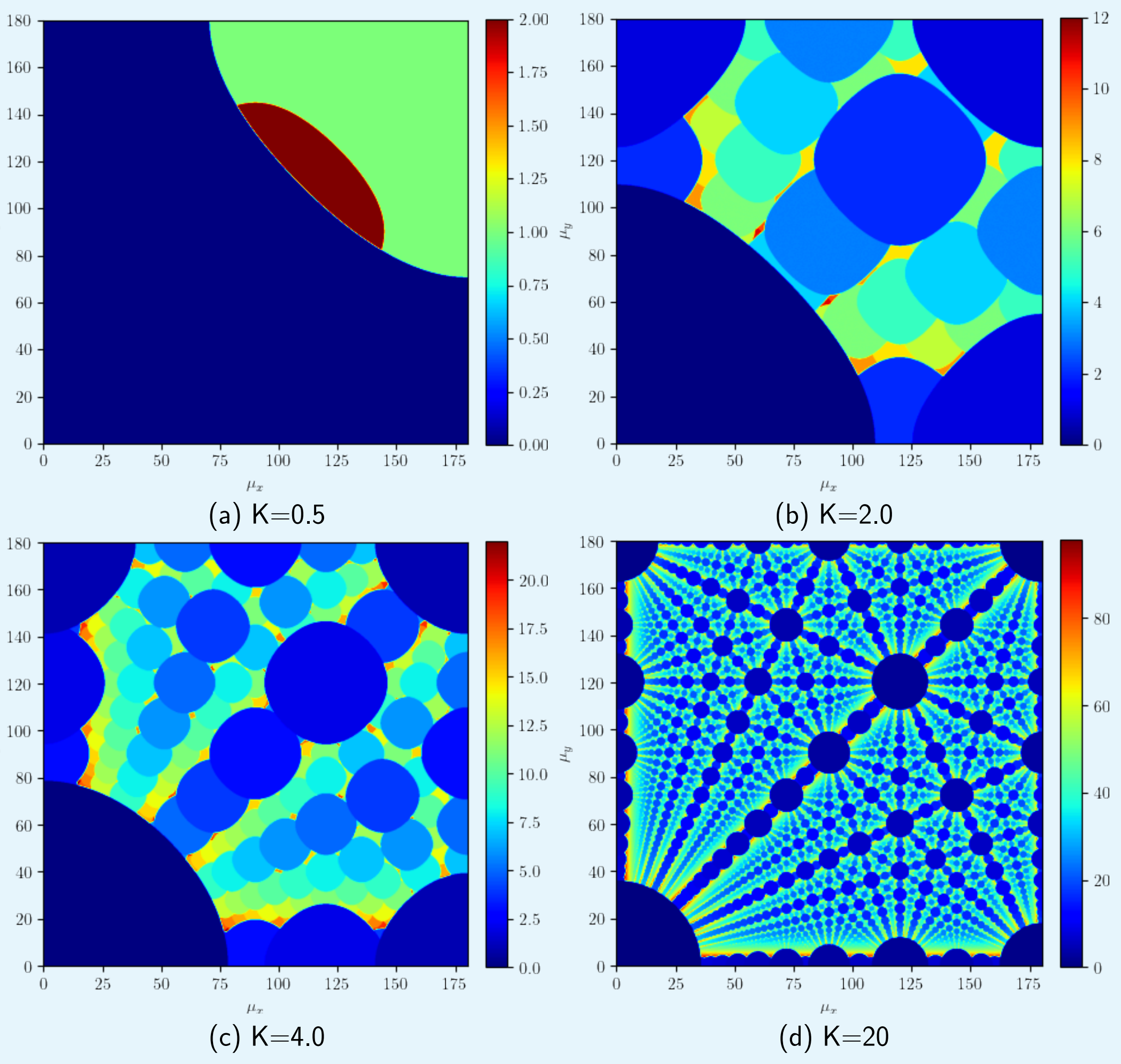
Choices for the ESSnuSB AR

- To have a complete accumulation in ESSνSB AR we need to inject and store ε_{100} for a total of 600 turns with no loss.
- Work with fixed injected beam parameters to allow the use of collimators to precisely define the injected beam transverse emittances with some freedom on the C-S parameters in the transfer line (injected beam control).
- Allow an evolution of the ring $\beta_{x,y}$ C-S parameters to satisfy Eq. 1 all along the injection process but keeping constant tunes (phase-advances).
- Fix the injected beam and ring α C-S parameters and beam angles to zero ($\alpha_r = \alpha_i = x'_r = x'_i = 0$).
- make an optimization leading to equal stored emittances in both transverse planes (round beam), leading to a 45° septum and the same H and V dynamics

The first order analysis consists in determining the evolution the distance of beam-center to the septum (DS_{bc}) assuming a constant beam size. Considering that the minimum condition for no loss is that $DS_{bc}(n) < DS_i = \sqrt{2}dx_i$ this leads to

$$\cos(n\mu_x) + \cos(n\mu_y) < 2\frac{K(n)-1}{K(n)+1} \quad (3)$$

where $K(n) = dx_{co}/dx_i$, with dx_{co} and dx_i defined in Fig. [1].

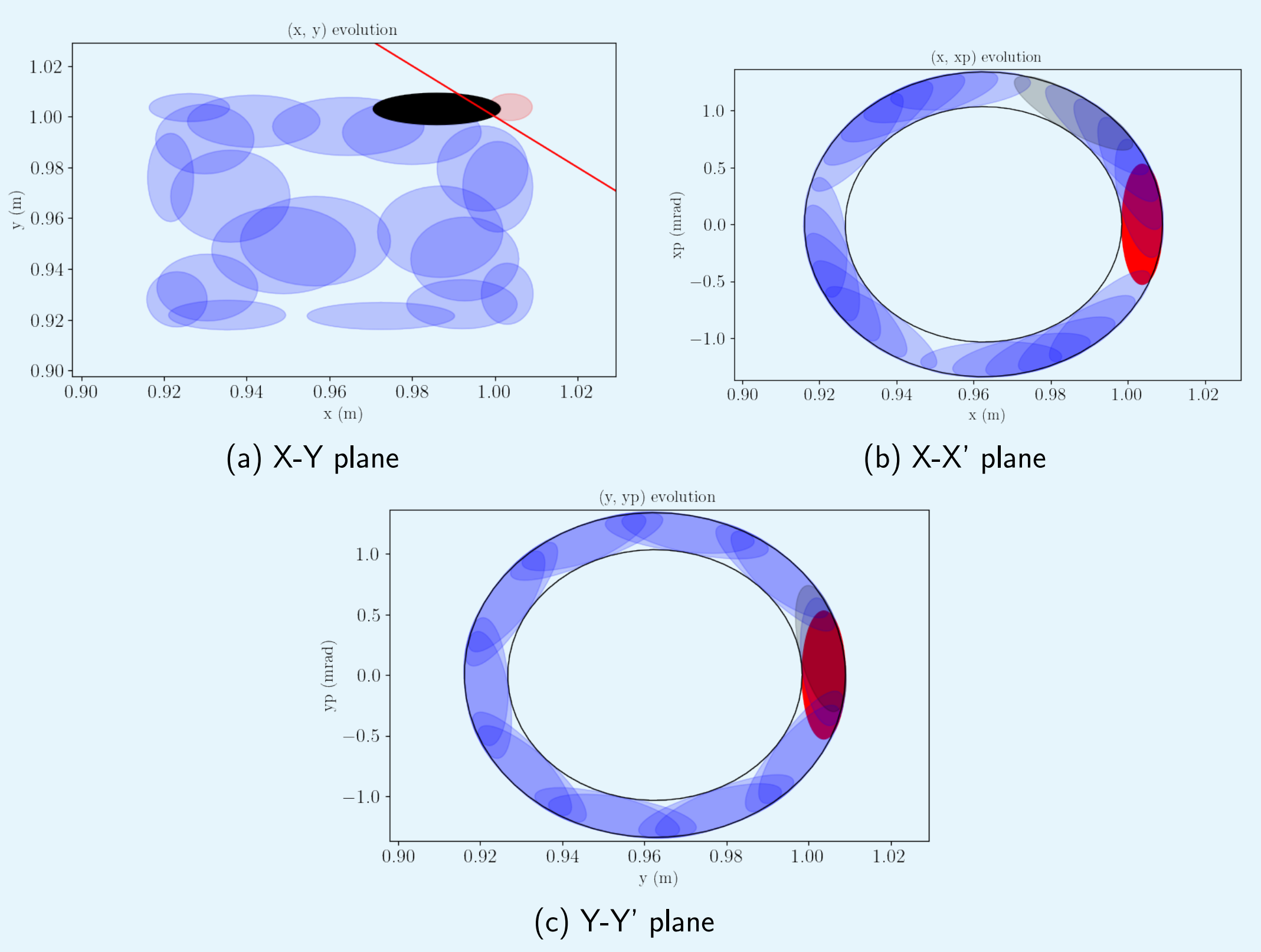


(a) K=0.5 (b) K=2.0

(c) K=4.0 (d) K=20

Figure 2: 3D NTBL plots in the tune diagram using eq. 3, K from 0.5 (top-left) to 20.0 (bottom-right). Dark-blue for loss at first turn, red for the maximum NTBL values.

100% Emittance Injection Optimization



(a) X-Y plane (b) X-X' plane

(c) Y-Y' plane

Figure 3: Turn-by-turn evolution of the 100% emittance injected beam without closed orbit shift, $\mu_x = 87.23^o$, $\mu_x = 35.47^o$ and K=10. The red ellipse is the injected beam and the black ellipse is the lost beam and turn 19.

Optimization taking tune spreads into account

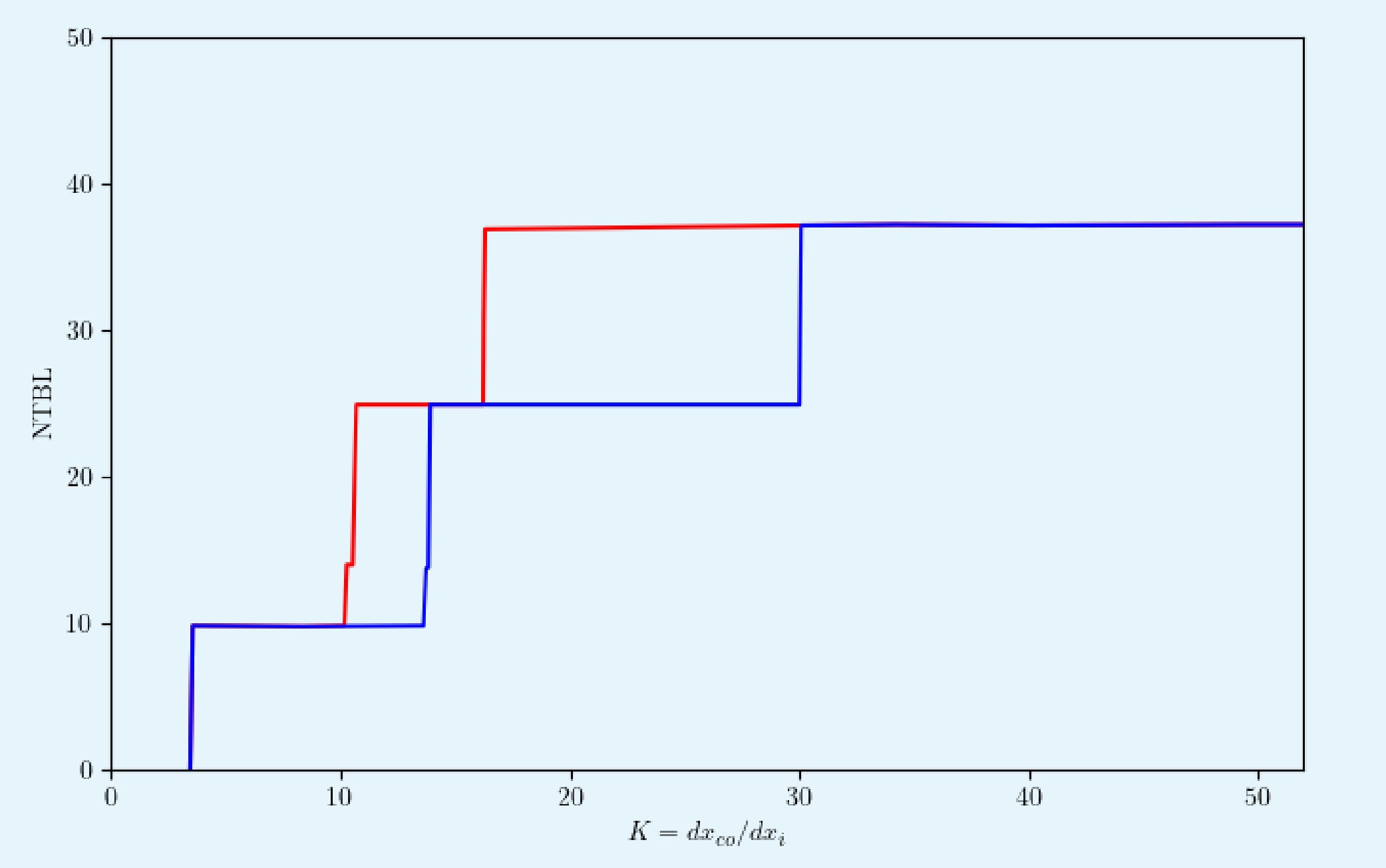


Figure 4: NBTL as a function of K for a working point with $(\mu_x, \mu_y) = (87^o, 36^o)$. Evolution for the nominal working point (red) and with $\pm 0.5^o$ errors on both tunes (blue).

Working point and K(0) selection

While the NTBL is the key parameter to minimize the needs of large closed-orbit shifts, the distance to the septum DS_{bc} when the beam is lost can be also taken into account to adjust the closed-orbit shift per turn in order to avoid the loss at turn NTBL + 1. This means that the minimum mean-closed-orbit shift per turn necessary to avoid a loss at turn n + NTBL + 1 is a figure of merit to be used to optimize the injection process. In other words we need to minimize

$$KSE = \frac{1}{K(N)} \sum_{m=K(0)}^{K(N)} \frac{DS_{sb}(m)}{NTBL(m)} \quad (4)$$

Closed-orbit route optimization

Optimization algorithm:

- turn N_0 is the turn at which the closed-orbit route is optimized for the previous injected turns,
- turn N_{min} is the turn at which the injected turn $N_i = N_0 + 1$ has a minimum distance to septum,
- Keep unchanged the closed orbit route up to turn N_0 in order to keep the optimized route and avoid possible beam loss of the previous injected turns,
- Minimize the next closed-orbit shift(s) from turn $N_0 + 1$ turn N_{min} decreasing the distance of the beam to the septum DS_{sb}.

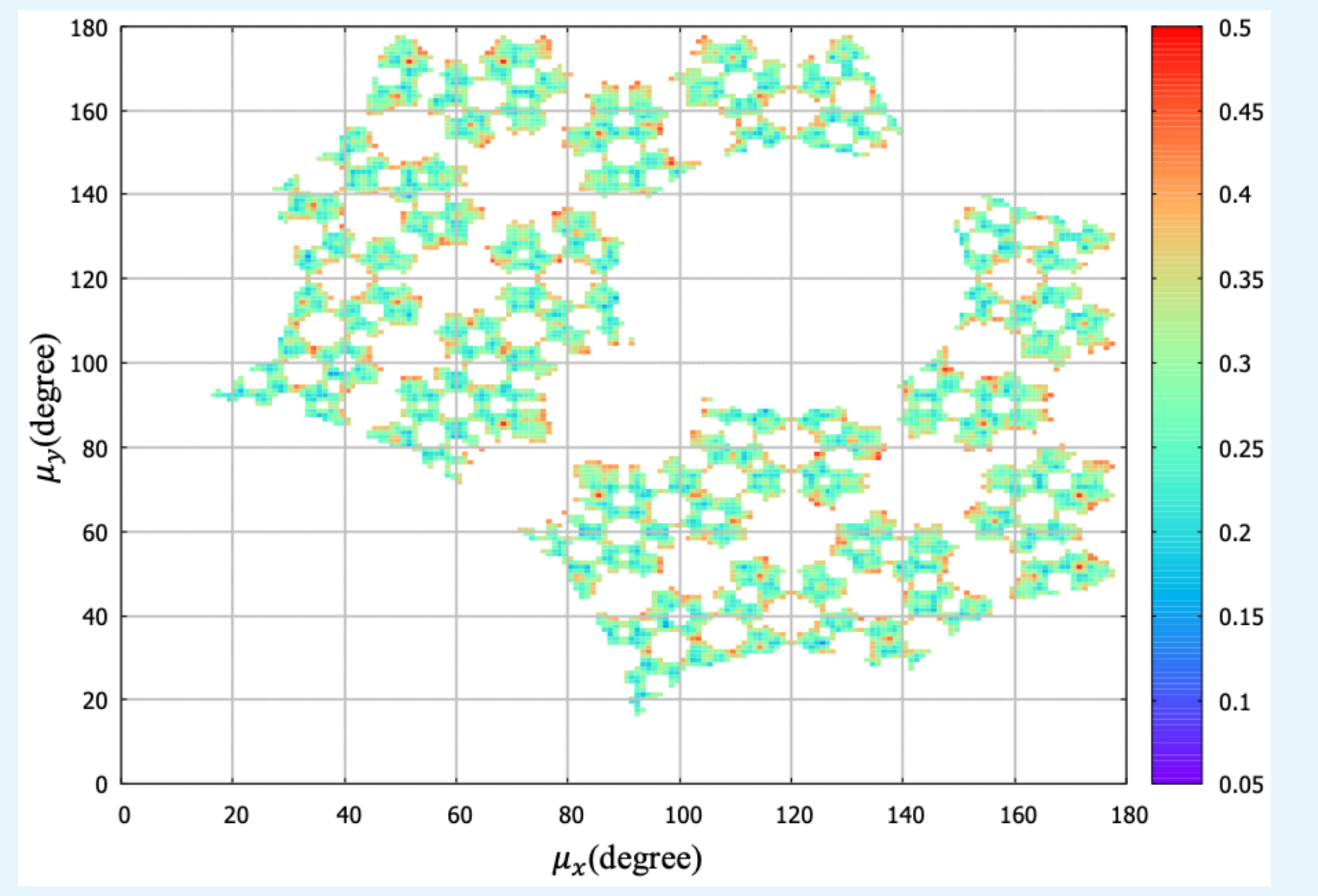


Figure 5: 3D plot of KSE for K between 4 and 42 step 0.1, μ_x, μ_y from 0 to 180^o step 1^o. Plot of the points with KSE values from 0.1 mm to 0.5 mm (maximum).

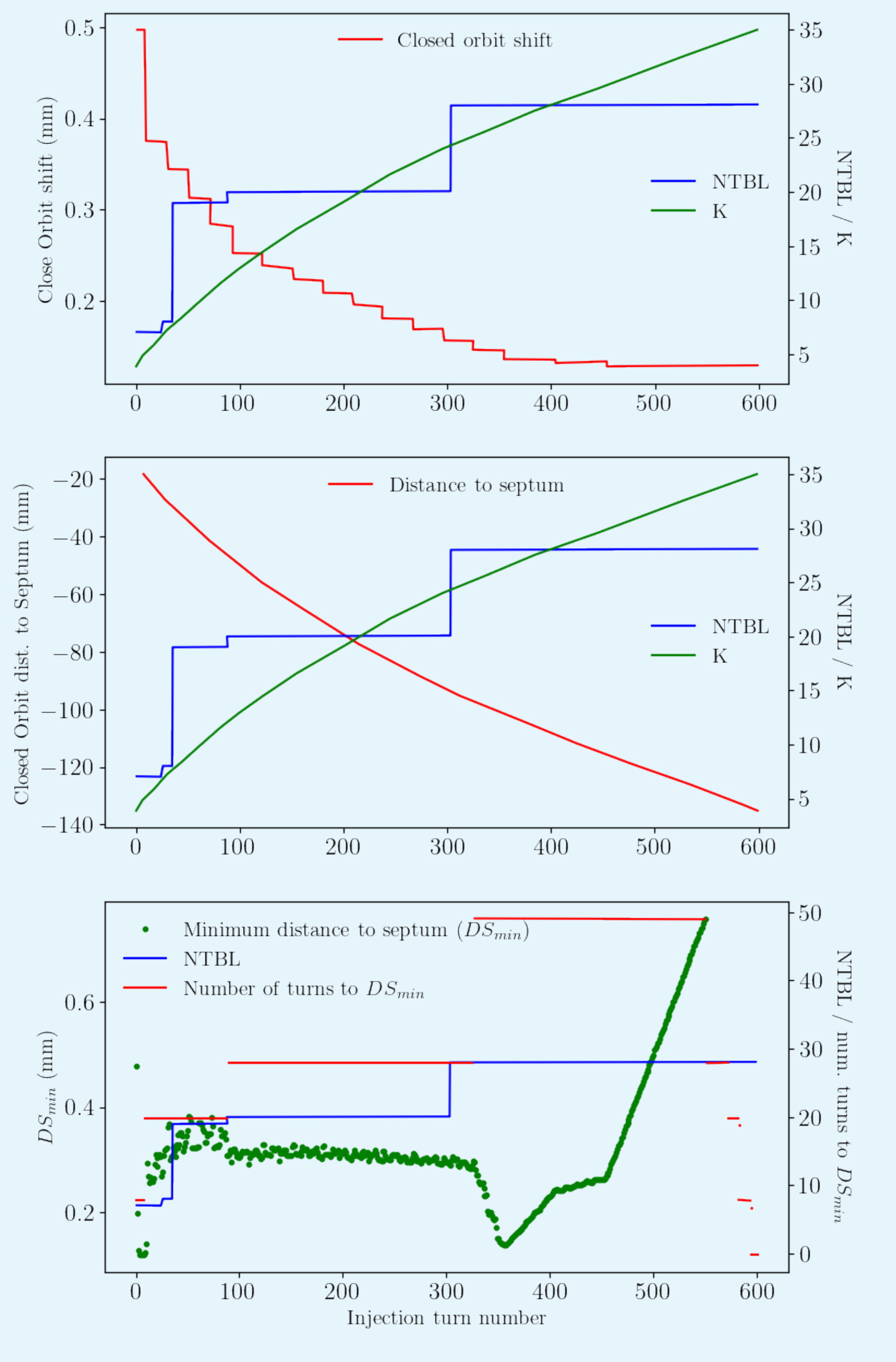


Figure 6: Optimized closed-orbit route, $(\mu_x, \mu_y) = (87^o, 36^o)$, tune error of $\pm 0.1^o$, $K(0) = 4.0$, $K(600) = 35.0$ and final emittance $\varepsilon_{x,y} = 136$ mm mrad.

CONCLUSIONS

- The implementation of LIO for ESSνSB can be beneficial since for this case the stored emittance is not a main concern.
- **The first steps of this study shows the NTBL as key parameter and that it is possible to optimize the 4D injection using only 3 parameters (the 2 tunes and K(0)).**
- Further work is necessary to use this findings and the method proposed to optimize the closed-orbit route in order to directly find the Liouvillian Injection Optimized parameters leading to a minimum stored emittance without loss on the 100% emittance.