Technical Note

Amman, June 4, 2006
Note: **I-2**

800 MeV Injection

M. Attal

Introduction

The layout of the injection channel from the booster to the main ring has already been designed for 800 MeV and full energy injection [1]. In this note we investigate more carefully the injection process at 800 MeV and the related issues concerning septum position, injection orbit bump amplitude, maximum kicker strengths, the convenient vacuum chamber aperture in the injection section, …etc.

Due to the shape and amplitude of the foreseen orbit bump, the injection efficiency was decreased by loosing particles at the internal wall of the vacuum chamber. Increasing the internal horizontal half aperture by 5mm along the injection section is the most effective cure to this problem.

A *single-kick* injection is the injection where the injected beam sees the kicker pulse just for one turn. This injection is the simplest one with small injection emittance (depending on the kicker amplitude) and 100% efficiency. In SESAME case (revolution time ~ 444 ns) it can be done with kickers of pulse duration of ~1μs.

On the other hand, a kicker pulse of 3μs, as originally foreseen, is easier to be realized but in SESAME case, this means that the injected beam will see the kicker pulse for 3 turns resulting in *multiple-kick* injection. This injection process is more complicated and it has an impact on injection efficiency. Many solutions have been found to achieve 100% of injection efficiency.

Optimum β_x for the injection

The optimum injection β_{xi} is the value of β_x at the injection point in the ring that produces the minimum *injection emittance* created by the injected beam oscillation around the central orbit [2]. It is determined by the distance between the centers of the injected and stored beams D that is the oscillation amplitude at the injection energy. D is, in general, composed of the effective thickness of septum sheet, the number of r.m.s. values for the injected beam n_i and for the stored one n_s.

$$D = S_{eff} + n_i\sigma_i + n_s\sigma_s \qquad (1)$$

In the injection calculations for SESAME, 3r.m.s. values (n_i = 3) for the injected beam and 4r.m.s. values (n_s = 4) for the stored beam are assumed.

At 800 MeV, $4\sigma_s$ = 1.062mm, with a booster emittance of 180 nm.rad and an energy spread of 3.82 10^{-4}. If we assume at the septum exit a dispersion fully matched and a S_{eff} value of 2.5mm, eq. (1) gives an optimum β_{xi} = 5.92m which implies $3\sigma_i$ = 3.157mm.

On the other hand, at 800MeV a strong increase in the energy spread of the stored beam has to be expected due to different causes. To take this into account with some safety margin, the beam parameters at 2.5GeV are considered (the energy spread is ~3 times larger and the emittance is ~9 times larger than the nominal values at 800MeV). In this case $4\sigma_s$ = 3.317mm and the optimum β_{xi} =

5.15m. Consequently $3\sigma_i$ = 2.952mm. The injection emittance versus optimum β_{xi} in both cases is shown in Fig. 1.

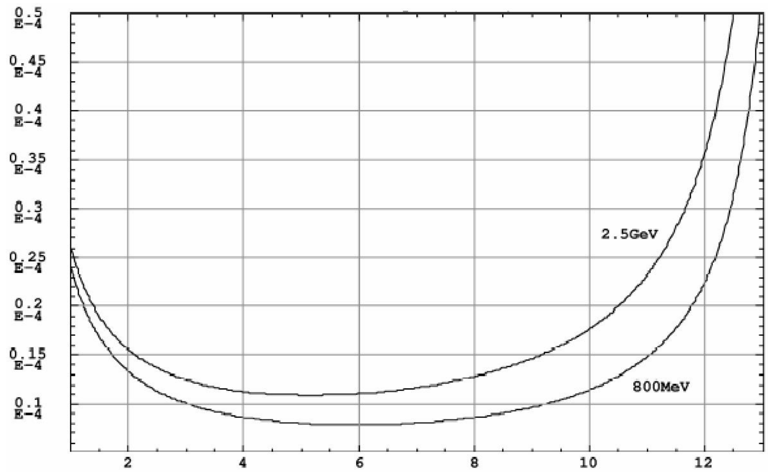

Figure 1: Injection emittance (m.rad) versus optimum β_{xi} (m).

Injection orbit bump

The kicker positions in the previously suggested 4-kicker bump in the ring [1] were a little bit modified: now all the kicker centers are at 55cm from the center of the adjacent SF sextupole, while the thin septum exit is located in the center of the *Long* straight (see Fig. 2).

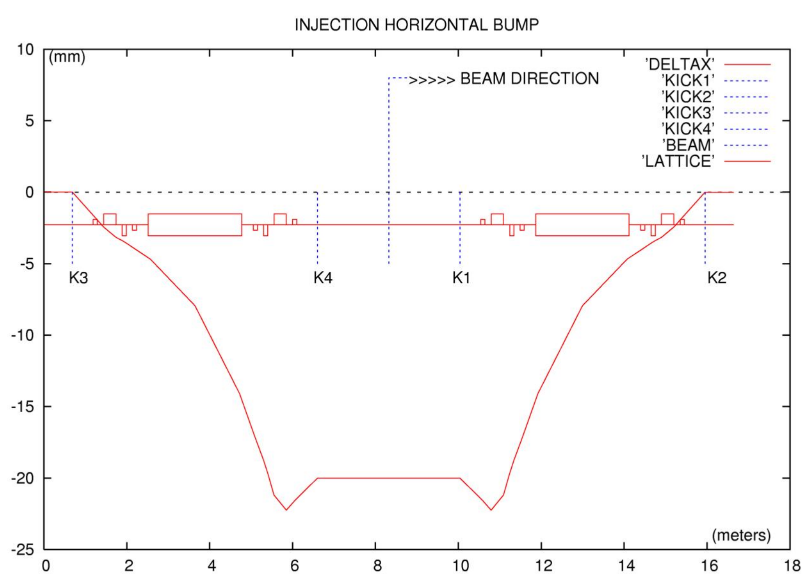

Figure 2: Layout of injection septum and kickers.

The septum sheet position X_{septum} was calculated, taking the nominal chamber horizontal half-aperture ($X_{chamber}$ = 35mm) as a reference:

$$X_{septum} = X_{chamber} \text{ - septum pipe diameter - septum sheet thickness =}$$

$$= 35 - 9 - 2.5 = 23.5\text{mm}.$$

however, for better gas scattering lifetime, it was decided to put the septum sheet at 25mm from the chamber center, consequently $X_{chamber}$ has to be increased to 36.5mm in the injection section (Fig. 3).

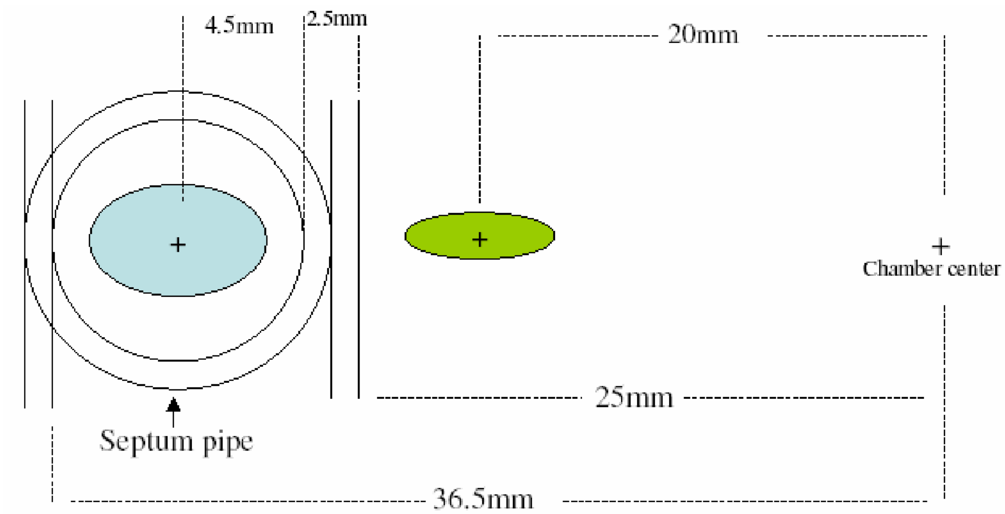

Figure 3: A sketch shows the septum pipe with the injected beam $6\sigma_i$ (blue) inside and the bumped stored beam $8\sigma_s$ in the chamber (green).

The bump amplitude was determined by subtracting $4\sigma_s$ (at 2.5GeV) from X_{septum} to be 21.683mm, but for safety margin, a 20mm bump has been considered.

The kicker strengths for a -20mm bump are given in Table 1 for the linear (without sextupoles) and nonlinear (with sextupoles) cases. In the nonlinear case, the kicker strengths are slightly modified to compensate for the sextupole kicks. Sextupole effect on the oscillating injected beam is not so strong and therefore injection dynamics is comparable in linear and nonlinear cases. All our results refer to the case with sextupoles on.

Table 1

Kicker strength (mrad)	K1	K2	K3	K4
Without sextupoles	-2.936	-3.19	-3.19	-2.936
With sextupoles	-2.872	-3.242	-3.242	-2.872

Septum and kickers in BETA code

In BETA code septum and kickers are represented by thin lens elements. The ring structure begins with the thin septum exit where all the injection tracking will be shown for many turns. Kickers strengths are variable simultaneously with time. According to their sequence in the lattice (Fig. 2), Tab. 2 displays the relative kicker's amplitudes at successive turns for half sine wave 3 μs kickers pulse length.

Table 2: Relative Kickers Amplitude.

TURN	K3 & K4	K1 & K2
1	.8938	1
2	.5979	.8938
3	.175	.5979
4	0	.175

Injection in the main storage ring

Tracking injected beam

To study the injection dynamics with BETA code, we launch 100 particles with effective emittance = $n_i^2\ \varepsilon_i$ (ε_i is the booster emittance 180nm.rad and n_i =3), distributed around $3\sigma_i$ of a Gaussian distribution, with beam size controlled by β_{xi}. These particles are injected at an amplitude X_{inj} and angle X'_{inj} and tracked in x-x' phase-space for 10turns. In case of any loss, the code gives the number of lost particles, from which we can evaluate the injection efficiency.

The main target of the injection process is a high injection efficiency, which depends on the injected beam amplitude, angle and size in addition to the multiple kick structure. Injecting the beam on the pulse crest, at an amplitude X_{inj} = -32mm (Fig.3) from the chamber center, with zero angle X'_{inj} = 0 and using a 20mm-amplitude bump are the default injection conditions in SESAME. Injected beam size ($3\sigma_i$) can be changed, according to injection conditions, up to 4.5mm (radius of septum pipe) making the maximum β_{xi} = 12.27m.

Loosing particles at chamber wall on the first turn

Injected particles get lost by two mechanisms: by the chamber wall at the beginning of the first turn and by septum at the end of the first turn in case of multiple-kick injection.

Due to the shape of injection bump the beam coming from the septum is kicked by K1 toward the vacuum chamber wall. At the default injection conditions, this causes some particles to get lost on the internal chamber wall. Increasing the chamber half-aperture $X_{chamber}$ in the injection section is the cure to this problem.

$X_{chamber}$ has benn increased gradually until it had no effect on injection efficiency. Moreover, increasing the injected beam size (by increasing β_{xi}) needs a larger value of $X_{chamber}$ as can be seen from Fig. 4. With β_{xi} = 12.27m (which gives the maximum beam size) the minimum needed $X_{chamber}$ = -38.7mm, but for safety -40mm is a more convenient choice.

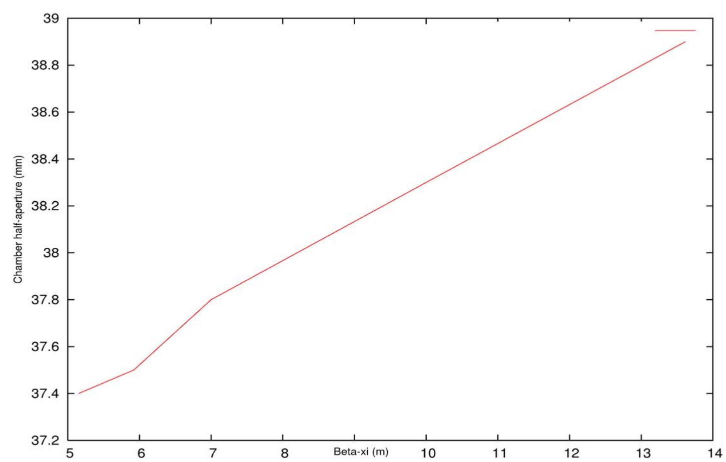

Figure 4: The needed chamber half-aperture versus β_{xi}.

The increase in $X_{chamber}$ has to be added to the inner half of chamber as a slot of width X= 5mm. This slot will be vertically limited to half-height Z= 7mm due to the sextupole poles. Nevertheless, tracking the injected beam in the vertical phase space, for fully matched β_{zi}, showed that we can even minimize the half-height up to Z= 3.5mm without loosing any particle.

A horizontal taper can begin at the defocusing q-pole after the septum, in order to go back to the normal chamber dimension before the bending magnet.

The increase in $X_{chamber}$ can be avoided by injecting the beam with some angle toward the chamber center. The minimum needed angle at X_{inj} = -32mm, β_{xi} = 6m is X'_{inj} = 0.4mrad. Moreover, with small values of β_{xi} the beam can be injected at smaller amplitudes X_{inj} and this gives better results.

Injection with short kicker pulse (a single-kick injection)

Using a short pulse of 1μs is the best solution for more efficient and straightforward injection. The injected beam sees just 0.175 of the maximum kick amplitude when it comes back to the septum after one turn, consequently, it will be enough far from the septum sheet. This single-kick injection results in a small injection emittance, using suitable β_{xi}, and 100% efficiency. Fig. 5 shows this type of injection for an injection bump of –20mm.

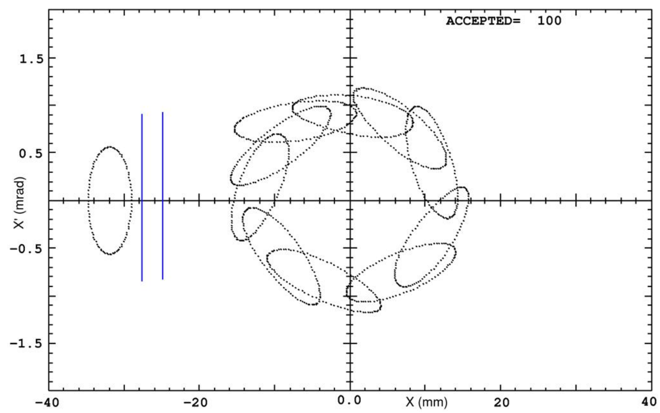

Figure 5: A single-kick injection with bump amplitude= -20mm and β_{xi} = 5.15m.

On the other hand, the booster beam is injected as a train of bunches about 0.15μs long. The short length of the pulse makes a difference 0.03 in the kick seen by the ends and the middle of the train. The resulting difference in oscillation amplitude is 0.55mm.

Even with a 1.5μs-pulse the single-kick injection process can be done easily as shown in Fig. 6. The beam sees 0.5979 of the maximum kick after one revolution time.

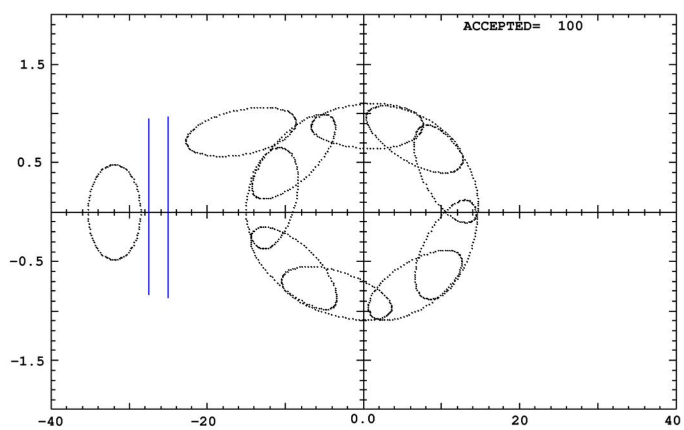

Figure 6: A single-kick injection with bump amplitude= -20mm and β_{xi} = 7m.

The possibility to have a 1μs-pulse kicker needs to be investigated. On the other hand, a 3μ pulse is easier to get but it makes the injection more complicated and the injection efficiency more critical, nevertheless a successful injection can be done.

A multiple-kick injection

In case of multiple-kick injection, using the default injection conditions (taking into account the new $X_{chamber}$ = -40mm) some particles get lost at the septum sheet. Due to the small decrease in the bump amplitude, part of the beam hits the septum at the end of the first turn, which is the most critical turn. On the 2^{nd} turn, the bump amplitude will be smaller in addition to the beam movement away from septum due to the tune-based oscillation.

The maximum injection efficiency that can be achieved is with β_{xi} = 12.27m.This is shown in Fig. 7 where the blue lines represent the septum sheet thickness. To the left of septum sheet the beam is injected at X_{inj} = -32mm, X'_{inj} = 0. Beam at the end of the 1^{st}, 2^{nd} and 3^{rd} turns is marked. Out of 100 injected particles, 71 are accepted. This implies an injection efficiency of ~ 90.6%. Many solutions have been found to achieve 100% efficiency.

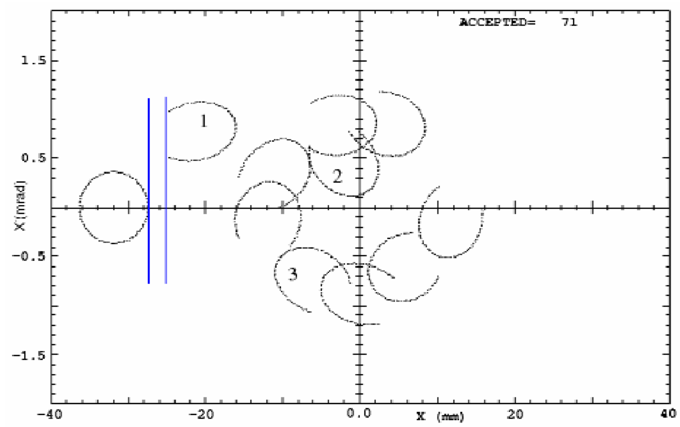

Figure 7: Injection on the default conditions

a) Injection with angle

An efficiency of 100% can be achieved for X_{inj} = -32mm by injecting the beam with some angle. The minimum angle is X'_{inj} = 0.15mrad whith the smallest injection emittance while the maximum one is X'_{inj} = 1.1mrad with the largest injection emittance. Out of this range, there will be particle loss at the septum. Both cases can be seen in Fig. 8.

To get smaller injection emittance, β_{xi} can be set at 5.92m. This allows an injection at X_{inj} = -30.657mm. In this case, 0.27mrad ≤ X'_{inj} ≤ 1mrad. Fig. 9 shows this injection scheme.

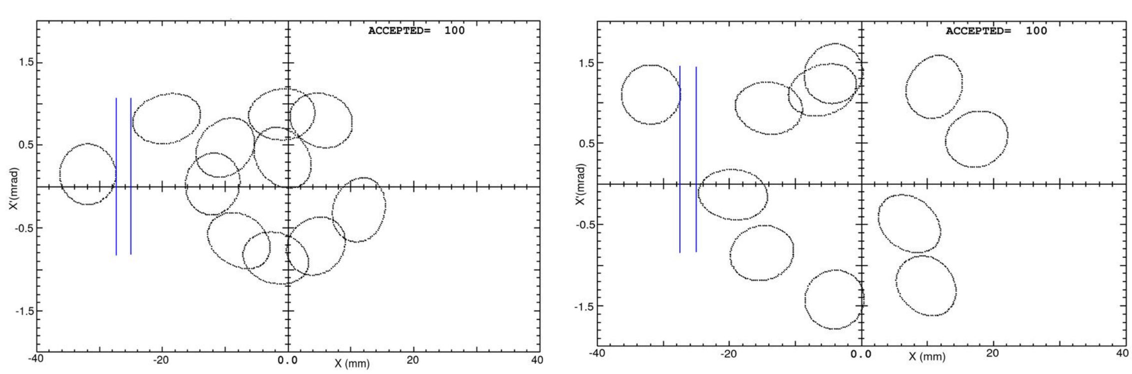

Figure 8: Injection with angles X'_{inj} = 0.15mrad (left) and X'_{inj} = 1.1mrad (right).

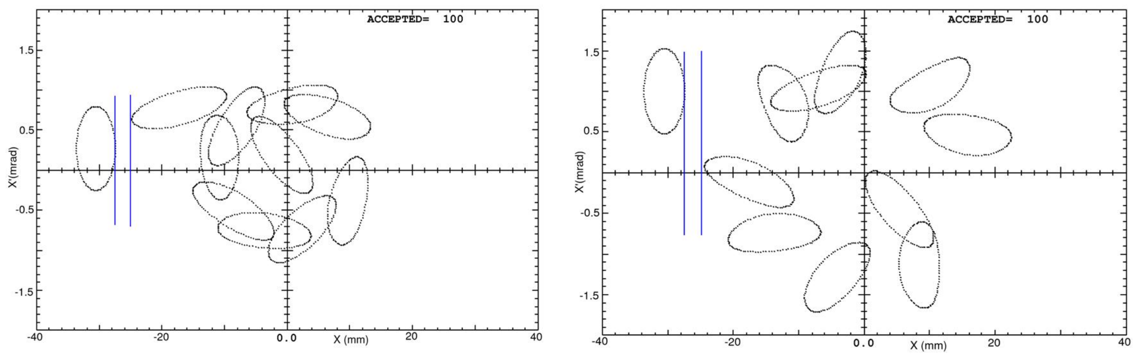

Figure 9: Injection at X_{inj} = -30.657mm, with X'_{inj} = 0.27mrad (left) and X'_{inj} = 1mrad (right).

b) Injection with different horizontal tune

The position of the injected beam in X-X' phase-space at the end of the first turn can be controlled by changing the fractional part DQ_x of the horizontal tune. In SESAME DQ_x =.23 which means that the injected beam will come back close to its first position after ~ 4turns. Increasing DQ_x decreases the number of turns needed for the beam to come back close to its initial position, and this takes the beam farther away from septum at the end of first turn. DQ_x.=.29 is a good solution to achieve 100% efficiency of injection at the default injection conditions as can be seen from Fig. 10.

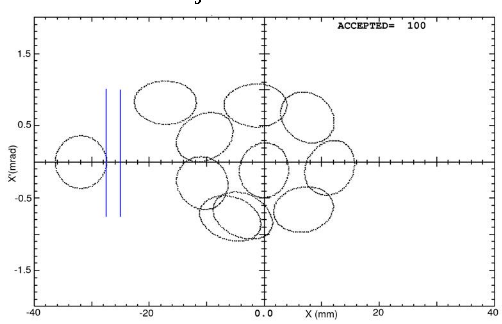

Figure 10: Injection with tunes (Q_x = 7.29, Q_z = 6.19) and β_{xi} = 12.27m.

The minimum β_{xi} that could be used for 100% efficiency was 6.3m, which allows to inject the beam at X_{inj} = -30.752mm. The resulting injection emittance was smaller in this case (see Fig. 11).

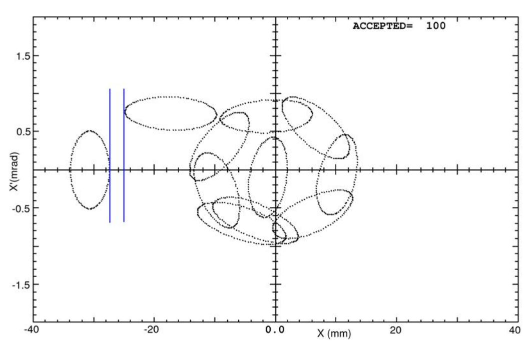

Figure 11: Injection with tunes (Q_x = 7.29, Q_z = 6.19) with β_{xi} = 6.3m

c) Injection after the crest of the kicker pulse

If we inject on the 3ms kicker crest, the beam will see 0.89 of the kick when it comes back to the septum after one turn. This could not help in taking the beam enough away from the septum in the case of -20mm bump. However, when we inject at 0.89 of the kick amplitude (i.e. 0.444μs after the crest time) the beam will see 0.598 of it when it comes back to the septum and therefore the beam will be enough far from the septum. Injection after crest in the case of -20mm bump is shown in Fig.12.

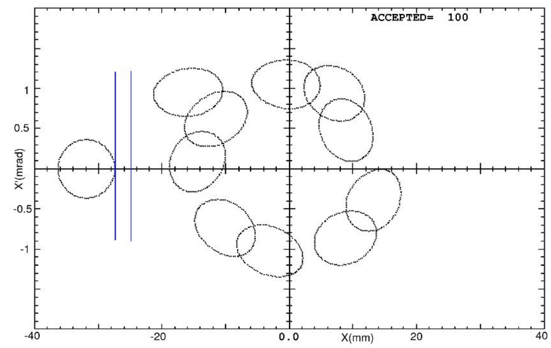

Figure 12: Injection at 0.444μs after crest, with β_{xi} = 12.27m.

The injection emittance increases in this case due to the larger distance D between the centers of injected and stored beams. However, with smaller β_{xi} it could have some decrement.

It may be worth to note that in this case, we injected with bump amplitude of -17.8mm and after one turn, the bump became -11.96mm. This is not equivalent to the case when we inject on the crest of -17.8mm bump since after one turn it will be -15.84mm.

d) Injection with smaller bump amplitude

Injection with smaller bump amplitude is another solution to get 100% efficiency for X_{inj} = -32mm and X'_{inj} = 0mrad. The maximum bump amplitude of -16mm was suitable to achieve this goal. This is in agreement with the last paragraph of the previous point. Fig. 13 shows this injection with β_{xi} = 12.27m.

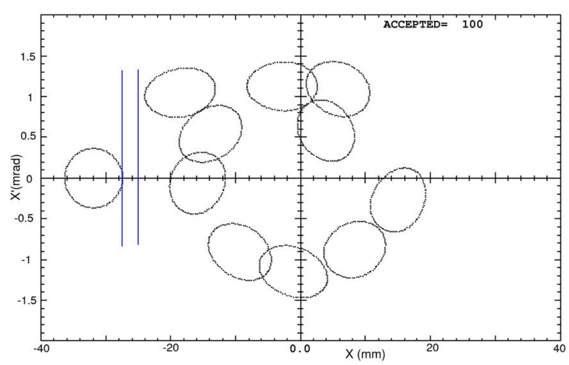

Figure 13: Injection on the crest with bump amplitude= -16mm and β_{xi} = 12.27m.

Conclusions

In principle, the injection into SESAME storage ring can be done successfully with high efficiency 90%, nevertheless a 100% efficiency can be achieved in many ways. As the oscillation amplitude of the injected beam is concerning, injection with angle or with different tune could be the best cases for small oscillation amplitude.

A shorter kicker pulse duration of 1÷1.5μs is preferable.

References

[1] M. Attal & A. Amro, SESAME Technical Note **I-1**, April 2005
[2] A. Streun, SLS booster-to-ring transfer line optics for optimum injection efficiency.