ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP22

ON LIOUVILLIAN HIGH POWER BEAM ACCUMULATION

J.-M. Lagniel[1,2], N. Milas[1,*], M. Eshraqi[1]
[1]European Spallation Source ERIC, Lund, Sweden
[2]Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France

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) [1], presently under construction in Lund, Sweden, will be the world's brightest neutron source, powered by a 5 MW proton linac. The linac accelerates proton pulses to 2 GeV, at a repetition rate of 14 Hz and a duty cycle of 4 %, before transport to the target station. The RF cavities at ESS can accept up to 10 % duty cycle, which means that it has the capability to provide an additional 5 MW of beam power. To this end, the ESS linac can, with moderate modifications, be used for the production of a very intense neutrino beam [2]. The ESSνSB project studies this possibility and a possible upgrade to the facility, which includes adding a H^- source and extra accelerating cavities for the linac, a transfer line and an accumulator ring (AR) that would then provide short proton pulses to the neutrino targets.

The main goal of this study is to analyse the possibility to inject protons from the linac directly into the accumulator using a 4D Liouvillian multi-turn accumulation process. The motivation is to analyse the advantages and drawbacks of such a choice in the ESS-specific case, considering the 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 and the substantial increase in complexity of the control and safety system. Also, an accumulation at higher energy, which is the case of the ESSνSB project at 2.5 GeV, has the advantages to be done with lower emittances and lower space-charge effects compared with its counterparts in US (SNS) and Japan (J-PARC).

* natalia.milas@ess.eu

METHOD

The code developed for Liouvillian Injection Optimization (LIO) uses a formalism similar to the one used in MISHIF [3]. While the goal of MISHIF is to optimize the multiturn injection parameters in order to accumulate a maximum of beam in a given ring acceptance the goal of LIO is to minimize the ring acceptance needed for no losses, in short, to get 100 % accumulation efficiency in an emittance as small as possible. In other words, the ring acceptance is an input parameter for MISHIF while it is an output parameter for LIO. The reason for this choice looks obvious since the objective is to accumulate a 5 MW beam, with no loss budget considering this huge beam power.

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 $\varepsilon_{100} = 26 \cdot \varepsilon_{rms} = 2.8$ mm mrad in both planes [4]. 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 (see Refs. [3] and [4]) 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, $(x_{co}(n), x_{co}'(n))$ the closed-orbit position and angle at turn n.

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. In order to investigate this possibility few choices are needed. The first choice is to 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).

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP22

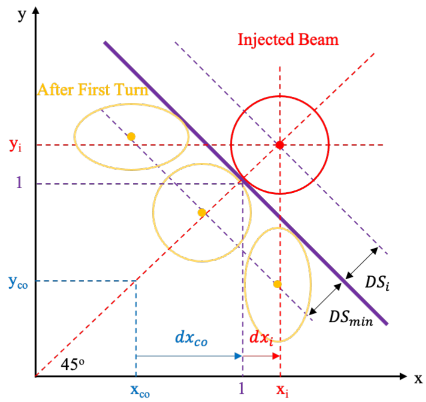


Figure 1: Geometry and parameter definitions for the injected and stored beams.

The second choice is to allow an evolution of the ring $\beta_{x,y}$ C-S parameters to satisfy Eq. (1) all along the injection process (as done for the heavy ion inertial fusion projects [5]), but to keep constant tunes (phase-advances). The third choice done to simplify the study in this ex-ploratory phase is to satisfy Eq. (1) during the injection process, fixing the injected beam and ring α C-S parameters and beam angles to zero ($\alpha_r = \alpha_i = x'_r = x'_i = 0$). The fourth and last choice is to make an optimization leading to equal stored emittances in both transverse planes (round beam as in [2]), leading to a 45° septum and the same H and V dynamics [4].

First Order Analysis

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 $DS_{bc}(n) < DS_i = \sqrt{2}dx_i$ (see Fig. 1), this leads to

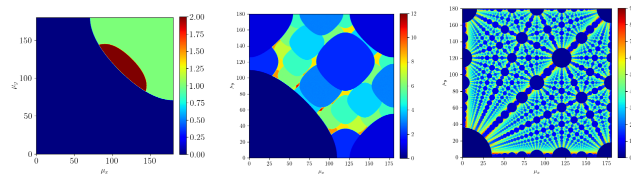
$$\cos(n\mu_x) + \cos(n\mu_y) < 2\frac{K(n)-1}{K(n)+1}, \tag{3}$$

where $K(n) = dx_{co}/dx_i$, with dx_{co} and dx_i defined in Fig. 1. Computing Eq. (3) with increasing n but a constant $K(n) = K(0)$ allows to compute the "Number of Turns Before Loss" (NTBL) without closed-orbit shift, which is a function of only 3 parameters: μ_x, μ_y and $K(0)$. This NTBL value is a very good criterion to optimize the accumulation efficiency since maximizing it is an obvious way to minimize the amplitude of the closed-orbit shifts, thus to minimize the stored emittances.

Symmetries in the Tune Diagram

Another outcome of Eq. (3) is the odd and even symmetries with respect to μ_x and $\mu_y = 180°$, meaning that the injection optimization of the 3 parameters can be done in a limited tune diagram area, e.g. in the triangle (μ_x ,μ_y) = (0, 0), (0, 180°), (180°, 180°). Figure 2 presents NTBL 3D plots for increasing $K(0)$ values, showing the symmetry with respect to the $\mu_x = \mu_y$ line and how the pattern evolves.

One must also highlight the striking resemblance between the last plot in Fig. 2 and the plots of the best accumulation efficiencies in the HIAF BRing [6]. It is worth to point out that the plot in [6] is a result from multi particle tracking simulations with space charge.



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

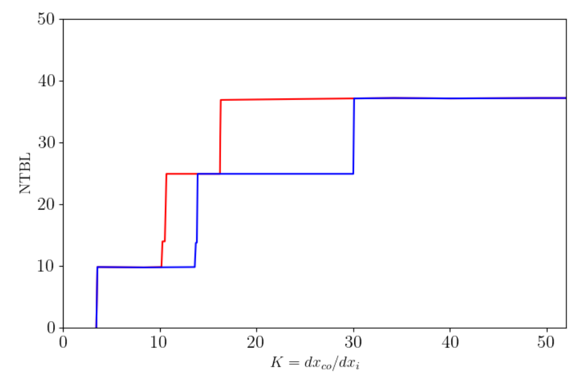


Figure 3: NBTL as a function of K for a working point with $(\mu_x, \mu_y) = (87°, 36°)$. Evolution for the nominal working point (red) and with ±0.5° errors on both tunes (blue).

100 % EMITTANCE INJECTION OPTIMIZATION

The "first order analysis" presented above is done with NTBL values considering the turn-by-turn evolution of the injected beam position and a constant beam size. The same analysis is now done taking into account the ε_{100} emittance turn-by-turn evolution. More accurate but similar results are obtained in this case, indicating that Eq. (3) has the right beam physics. The procedure used to compute the one-turn evolution involves the calculations of the ring transfer matrix, end turn beam positions, angles and C-S parameters and finally the calculation of the beam distance to septum [4].

Optimization Taking Tune Spreads into Account

Figure 2 and detailed studies in Ref. [4] show a high sensitivity to tune shifts, even low as 1°. The optimization is then done computing the turn-by-turn evolution of the beam with the nominal tunes plus 8 beams with a fixed error, to be adjusted taking into account tune shifts induced by space change or chromaticity. The optimization is always done considering the worst case. Figure 3 gives an example of NTBL reduction with ±0.5° errors.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP22

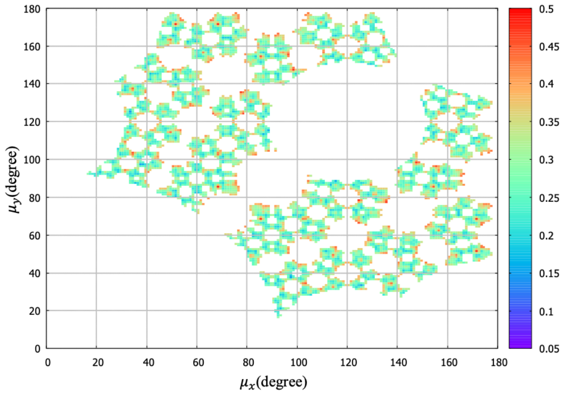


Figure 4: 3D plot of KSE for K between 4 and 42 in steps of 0.1, μ_x, μ_y from 0° to 180° in steps of 1°. Plot of the points with KSE values from 0.1 mm to 0.5 mm (maximum).

Working Point and K(0) Selection

Looking again at Fig. 2, one can notice that as K increases the size of the forbidden areas (blue and purple areas with NTBL = 0 or 1) decreases and that the positions of the highest NTBL areas (orange to red) shift. This means that, choosing to keep a fixed working point all along the injection process, the working point must be chosen maximizing the NTBL along the full injection process, from turn N=1 to N=600.

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

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

Equation (4) can be used to select a restricted μ_x, μ_y, $K(0)$ the computation of the "big-table" of stored emittances to be used to pick-up the final optimized values. Figure 4 shows how this technique is useful to minimize the size of this "big table", then to lower the computation time or to allow a finer exploration of the 3 parameters with tune spread, also only considering the $(0,0)$, $(0,180°)$, $(180°,180°)$ tune area.

Closed-orbit Route Optimization

Once the working point and $K(0)$ selection are done, the last step is to compute an optimized closed-orbit route leading to minimum stored emittances for each point, without loss, and again taking tune spreads into account. The best method developed today consists of a "step-by-step" correction of the closed-orbit shifts of injected turn groups [4]. Assuming that turn N_0 is the turn at which the closed-orbit route is optimized for the previous injected turns, and turn N_{min} is the turn at which the injected turn $N_i = N_0 + 1$ has a minimum distance to septum, then:

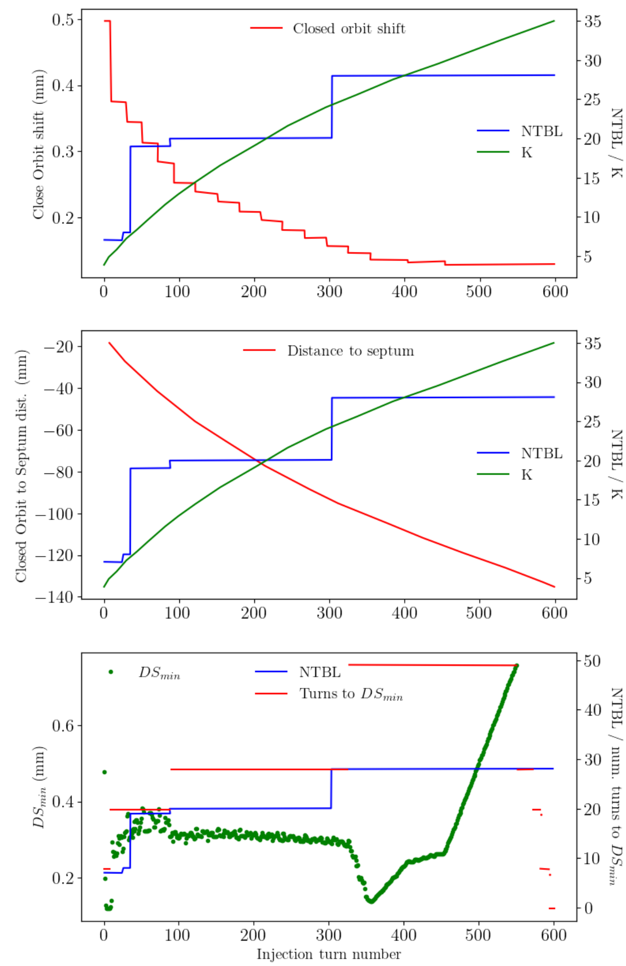


Figure 5: Optimized closed-orbit route, $(\mu_x, \mu_y) = (87°, 36°)$, tune error of ±0.1°, $K(0) = 4.0$, $K(600) = 35.0$ and final emittance $\varepsilon_{x,y} = 136$ mm mrad.

1. 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,
2. 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 shows a typical result with a well optimized closed-orbit route up to turn 450. The optimization procedure must be improved for the last injected turns.

SUMMARY AND FUTURE WORK

The implementation of LIO for ESSνSB could represent a major simplification on the ESS operation side. 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 LIO parameters leading to a minimum stored emittance without loss on the 100 % emittance. This future work will also allow to progress on the Liouvillian injection beam physics.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP22

REFERENCES

[1] R. Garoby *et al.*, "The European Spallation Source Design", *Phys. Scr.*, vol. 93, p. 014001, 2018. doi:10.1088/1402-4896/aa9bff

[2] A. Alekou *et al.*, "The European Spallation Source neutrino super-beam conceptual design report", *Eur. Phys. J. Spec. Top.*, vol. 231, pp. 3779–3955, 2022. doi:10.1140/epjs/s11734-022-00664-w

[3] C. R. Prior, "MISHIF: A code to optimize multiturn injection, A guide for users", STFC-RAL, Chilton, England, Internal Report, Aug. 2020.

[4] J.-M. Lagniel, "ESSνSB Liouvillian Injection Optimization", ESS, Lund, Sweden, Internal Report, Aug. 2023.

[5] C. R. Prior and H. Schoenauer, "Multiturn injection into accumulators for heavy ion inertial fusion", in *Proc. EPAC'96*, Sitges, Spain, Jun. 1996, paper MOP026G, pp. 2391–2393.

[6] L. P. Yao *et al.*, "Beam-loss driven injection optimization for HIAF-BRing in the presence of space charge", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 951, 2020. doi:10.1016/j.nima.2019.162876