

# APPLICATION OF UAL TO HIGH-INTENSITY BEAM DYNAMICS STUDIES IN THE SNS ACCUMULATOR RING\*

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## Abstract

The SNS Ring off-line parallel simulation environment based on the Unified Accelerator Libraries (UAL) has been implemented and used for extensive full-scale beam dynamics studies arising in high-intensity rings. The paper describes the structure of this environment and its application to the development and analysis of the SNS accumulator ring beam loss model including a complex combination of several physical effects.

## 1 INTRODUCTION

Designs and parameters of modern high-intensity machines, such as the SNS accumulator ring, impose new expectations on the beam dynamics studies. One of the major scientific and technical challenges is the extremely strict requirement on uncontrolled beam loss at  $10^{-4}$  level. In order to describe and analyze such low-level losses, one should closely reproduce all actual effects of a realistic machine. For addressing this task, we have employed the open simulation environment of the Unified Accelerator Libraries (UAL[1]). When we started this project, UAL had been already applied to several accelerators. However, unlike other UAL applications, the SNS Ring required a new combination of collective physical effects and dynamic processes. Then the new SNS-specific package has been implemented. Its development included the integration of the UAL infrastructure with three accelerator libraries (ORBIT, ACCSIM, and MB), deployment of this infrastructure on the MPI-based parallel facility, and the implementation of the injection framework. In the paper we describe the structure of the SNS simulation package and its application to complex beam loss studies.

## 2 UNIFIED ACCELERATOR LIBRARIES

The Unified Accelerator Libraries (UAL) is an accelerator simulation environment aiming to develop the realistic beam dynamics models including an unlimited combination of physical effects and dynamic processes. The goal has been achieved by introducing the open infrastructure where diverse accelerator approaches and programs are implemented as collaborative C++ libraries connected together via Common Accelerator Objects (such as Element, Twiss, Particle, *etc.*). At this time, the UAL 1.x off-line simulation environment joins six object-oriented accelerator programs (see Fig.1). A universal homogeneous interface based on the Perl extension mechanism allows scientists to combine and manage all

these C++ and Perl components in the single development and research environment. The high-level applications are built on the top of the project-specific Shell (or Façade) that consolidates and facilitates access to numerous low-level UAL interfaces and data containers.

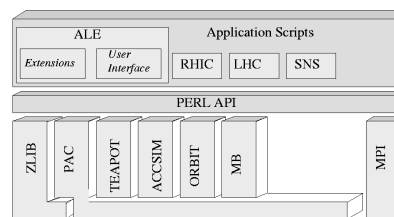


Figure 1: Unified Accelerator Libraries environment.

The same UAL infrastructure fits to the MPI-based parallel environment and has been recently deployed on the parallel cluster for efficient high-intensity beam dynamics modeling. Parallel versions of the time consuming algorithms (such as collective space charge effects) are implemented as ordinary C++ shared libraries and can be mixed together with other UAL sequential and/or parallel modules.

## 3 SNS SIMULATION ENVIRONMENT

According to the UAL approach, the SNS simulation environment has been organized as an additional package integrating together SNS-specific modules and extensions. The overall architecture of the SNS environment is illustrated in Fig. 2:

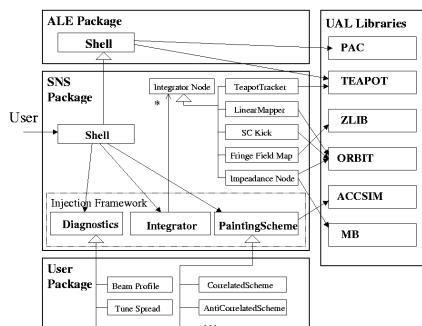


Figure 2: Structure of the SNS ring simulation package.

A physicist interacts with the SNS::Shell interface that encompasses a set of high-level MAD-like or TEAPOT-like commands. Most of these commands are project-independent, and inherited from the common class ALE::Shell. The SNS Ring multi-turn injection scenario

is considered as an extension of the present UAL environment and implemented directly in the SNS::Shell class. To facilitate the development and study of the SNS Ring applications, we have implemented the injection framework with three basis classes: SNS::Integrator, SNS::PaintingScheme, and SNS::Diagnostics. Each basis class originates an open collection of alternative approaches that can be selected in any combination with the instances of two other collections.

The SNS::Integrator class defines the common interface shared by all tracking modules used in the SNS simulation environment. Each tracking module is implemented as an array of integrator nodes associated with individual accelerator elements. This approach is based on the generic Element-Algorithm-Probe analysis pattern [2] that in the case of the tracking application divides all participated objects into three categories: Accelerator Node, Integrator Node, and Bunch of particles. Accelerator Node and Bunch are sharable containers of the UAL infrastructure, and Integrator Node is a SNS adapter to the relevant UAL module. The current SNS package encompasses the following collection of integrator nodes:

- Linear Mapper adapts the linear matrix approach. It is the fastest algorithm for propagating particles through accelerator elements without nonlinear magnetic fields.
- TEAPOT Tracker is a thin-element non-linear symplectic integrator allowing one to include non-linear magnet effects and misalignments in the SNS simulation model.
- SC Kick is an adaptor to the ORBIT space-charge module. It is based on a Particle-in-cell (PIC) method employing a bilinear distribution of macroparticles to the nodes of rectangular grid with subsequent use of Fast-Fourier-Transform (FFT) method to approximate the full non-linear space-charge force.
- Fringe Field Mapper is the ZLIB Taylor map extracted from the MARYLIE or “hard-edge” fringe field models.
- Impedance Node is an adaptor to the ORBIT and MB transverse impedance modules.

The second class, SNS::PaintingScheme, is associated with the injection painting that is a key process determining the beam dynamics and performance of the SNS accumulator ring. For selecting the optimal solution, several injection schemes (such as correlated, anti-correlated, etc.) have been extensively compared and explored. In the SNS package, all of them are represented by different Perl modules implementing the mandatory method *updateBunch* of the basis class SNS::PaintingScheme and a scheme-specific interface for defining injection parameters. Then the transition to a new injection approach requires only two steps. First, a user creates an instance of the selected module and defines its parameters, and finally, delegates this object to the injection framework that invokes the *updateBunch* method after each turn. This overall injection procedure is based on the ACCSIM approach and the SNS::Shell

framework extends it by providing the consistent mechanism for describing and implementing various injection scenarios.

The last class, SNS::Diagnostics, organizes the most dynamic part of the SNS simulation environment. During beam dynamics studies, developers and researchers deal with a big flow of various beam, lattice, and algorithm parameters which they desire to analyze with minimum effort and without affecting other application components. In the SNS application scripts, a physicist is able to select or implement arbitrary diagnostics approach and plug it into the injection painting process. Also the diagnostics model is designed after the Composite pattern allowing one to combine various diagnostics approaches together for gathering a wide spectrum of the relevant information.

## 4 APPLICATION

The UAL environment was successfully applied to beam dynamics studies of the SNS. Single-particle tasks, including such effects as kinematic non-linearity, non-linear tune-spread, dynamic aperture, and resonance driven diffusion maps, were extensively studied and reported in Refs. [3]-[4]. One of the major attractions of the SNS package is its applicability to beam dynamics studies with the space charge. It allows us to perform comprehensive study of various effects, as well as a complex combination of several effects simultaneously. Below, we list some of the high-current beam dynamics topics to which the SNS package was recently applied:

- Effect of space charge during transverse painting [5]
- Optimization of painting bump functions [6].
- Combined tune spread due to the space charge, chromaticity and other nonlinearities [6]-[7].
- Imperfection resonance crossing in the presence of space charge with corresponding choice of working points and intensity limitation [7]-[8].
- Effect of  $\frac{1}{2}$  coherent resonance crossing in the presence of high-order resonances.
- Coherent resonance crossing of coupling resonances.
- Collective instability due to the transverse coupling impedance [9].

An ability to study a complex combination of several effects enables us to have a realistic expectation for beam losses and intensity limitation. Here, we demonstrate the resonance driven beam loss for the two working points of the SNS. They are a result of a tune scan, keeping the working point fixed and increasing beam intensity. The imperfection errors are excited at a level slightly higher than expected to get a conservative estimate. The full 1060-turn injection is then performed for each of beam intensities with beam losses at the end of accumulation recorded for a specific acceptance. Figures 3-4 and 5-6 shows the tune spreads and corresponding resonance driven loss curves for (6.23,6.20) and (6.4,6.3) working points, respectively. The first working point in Fig. 3 is essentially free from resonance losses apart from some low loss due to the resonances above the working point

and chromatic tune spread. Here, the first-turn losses due to injection and H<sup>-</sup> stripping are omitted from the loss curve. For high beam intensities the tune are effectively depressed by the space charge. The only resonances up to the 4<sup>th</sup> order, which beam crosses during accumulation, are the difference resonances. As a result of the space charge coupling, the beam with approximately similar transverse beam emittances is not susceptible to the difference resonance. The intensity limitation for this working point is associated with the coherent beam response near the tune of 6.0, which limits beam intensity to slightly above  $N=2 \cdot 10^{14}$  at the energy of 1 GeV [10]. However, this limitation is due to the structure resonances and thus is very strict.

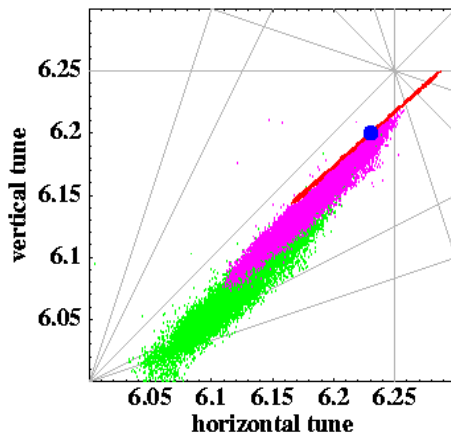


Figure 3: Tune spread for three beam intensities At the end of accumulation:  $N=0.1 \cdot 10^{14}$  (red),  $N=1.0 \cdot 10^{14}$  (pink) and  $N=2.0 \cdot 10^{14}$  (green).

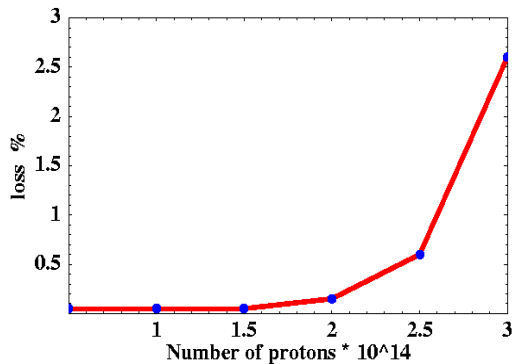


Figure 4: Loss curve for the working point (6.23,6.20).

For the working point (6.4,6.3), the loss curve demonstrates impact of each individual resonance crossed during accumulation. The strong loss at low intensity is due to the sum sextupole resonance at which the working point is located so that for real operation the tunes should be slightly adjusted to avoid this strong resonance loss. Other loss peaks are due to the 3<sup>rd</sup> and 4<sup>th</sup> order resonances which are crossed for higher beam intensity.

The losses due to these resonance are very strong, however, they are all imperfection resonances. With an appropriate correction schemes, which are available in the SNS, one can attempt to compensate such resonances. As a result, with successful compensation, the real loss for this working point happens only at a very high intensity due to the coherent beam response to the structure resonances, as shown in Fig. 6.

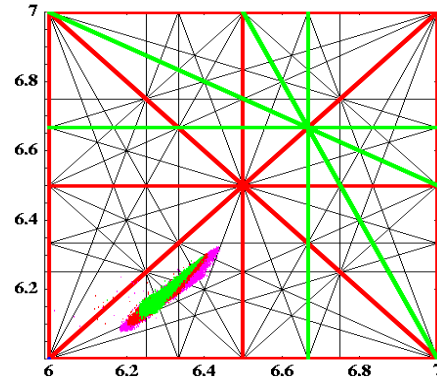


Figure 5: Tune space for working point (6.4,6.3), with 2<sup>nd</sup> order resonances shown in red, 3<sup>rd</sup> order structure resonance shown in green, and the imperfection resonances shown in black. The tune spread for a 2MW beam is shown for  $dp/p=0$ , 0.7 and 1% with green, red and pink colors, respectively.

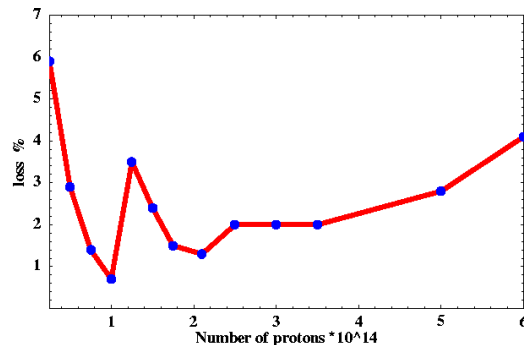


Figure 6: Loss curve for the working point (6.4,6.3).

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