MODELLING TRANSITION ENERGY CROSSING IN THE CERN PROTON SYNCHROTRON VIA TRACKING SIMULATIONS WITH XSUITE

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Abstract

The CERN Proton Synchrotron (PS) accelerates proton and ion beams over an energy range that leads them to cross transition energy in routine operation. To improve the understanding of the transition energy crossing in the PS, detailed particle tracking simulations using the Xsuite code are being set up. The configuration of the simulation model incorporates, in stages, the complete acceleration process through transition, the γ_t-jump scheme used operationally in the PS, and ultimately, the effects of direct space charge. Benchmarks with measurements are also shown.

INTRODUCTION

The CERN Proton Synchrotron (PS) is a key part of the CERN accelerator complex, serving as an injector for the Super Proton Synchrotron (SPS) and ultimately for the Large Hadron Collider (LHC), as well as a source of hadron beams for various fixed-target experiments. Proton beams are injected into the PS at an energy of 2 GeV and are subsequently accelerated to different final energies depending on their intended application. For beams directed to the SPS, the extraction energy is 26 GeV, whereas the ones delivered to the nTOF (neutron time-of-flight) facility [1] are extracted at 20 GeV.

The transition energy of the PS, being at approximately 5.6 GeV, must be systematically crossed for a wide range of beam configurations. A detailed understanding of beam dynamics in this operational regime is therefore essential.

In this work, a particle tracking model of the PS transition energy crossing is presented, implemented using the Xsuite framework [2]. The model incorporates the γ_t-jump scheme, which is operationally relevant for the PS, and includes an initial treatment of collective effects in combination with the transition crossing.

SIMULATING TRANSITION ENERGY CROSSING

During transition energy crossing, the slip factor $\eta = 1/\gamma_{\mathrm{tr}}^2 - 1/\gamma^2$ changes sign and in order to preserve longitudinal stability, the synchronous phase must be shifted according to $\phi_{s,\mathrm{above}} = \pi - \phi_{s,\mathrm{below}}$ [3]. This procedure is implemented in the simulation, as illustrated in Fig. 1: the energy program crosses transition, and at the crossing time a phase jump is applied such that the condition $\eta \cdot \cos(\phi_s) < 0$ is maintained, ensuring longitudinal stability.

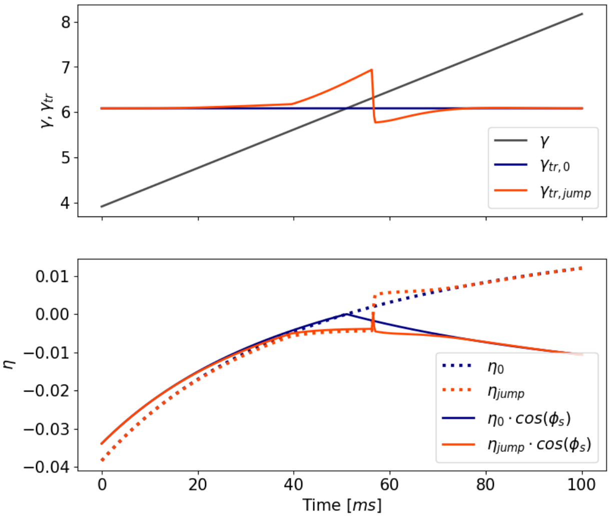

Figure 1: Transition energy crossing at the CERN PS, with and without γ_t-jump scheme. The energy ramp along with the transition energy are shown in the upper plot. The slip factors and their product with the cosine of the synchronous phase are shown in the bottom plot.

In the vicinity of transition, particles experience non-adiabatic synchrotron motion. The region in which the longitudinal dynamics no longer satisfy the adiabaticity condition can be characterized by the non-adiabatic time T_c, which depends on both machine and beam parameters. Tracking simulations have been performed over the time interval $t \in [-10T_c, 10T_c]$, with the transition crossing occurring at $t = 0$. The resulting evolution of bunch length and momentum spread is presented in Fig. 2.

Analytical predictions for the evolution of bunch length and momentum deviation during transition crossing, which account for non-adiabatic effects [4, 5], are also shown in Fig. 2. These predict a shortening of the bunch length and a corresponding increase in momentum deviation at transition. The particle tracking model reproduces these trends, with additional weak post-crossing oscillations attributed to longitudinal filamentation.

CERN PS γ_t-Jump Scheme

In the CERN PS, efficient transition energy crossing is achieved through the operational use of the γ_t-jump scheme [6]. In this approach, the value of γ_{tr} is dynamically modulated as the beam energy approaches transition. The resulting time dependence of γ_{tr} and the corresponding evolution of the slip factor η are illustrated in Fig. 1. As shown, γ_{tr} is adjusted such that the beam remains further

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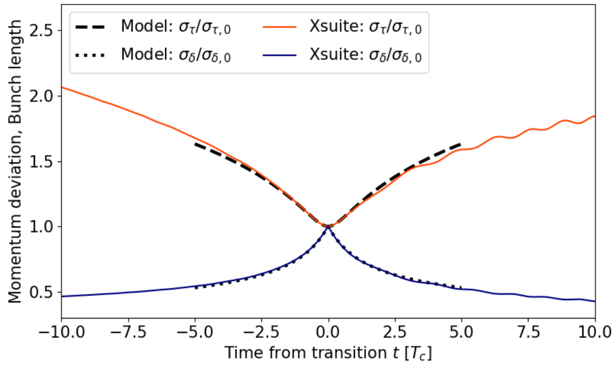

Figure 2: Normalized bunch length and energy spread around transition energy crossing (transition for $t = 0$). The non-adiabatic time $T_c \simeq 1.4$ ms is used as time unit. The analytical model predictions are shown along with the results from Xsuite tracking simulations.

from transition for a longer duration, while the actual crossing occurs significantly faster, with a rate reaching approximately 50 times the nominal value. This scheme reduces the time the beam spends in the non-adiabatic region, thereby mitigating several adverse effects associated with transition crossing. These include nonlinear longitudinal motion, longitudinal space-charge mismatch, and increased sensitivity to transverse instabilities [7].

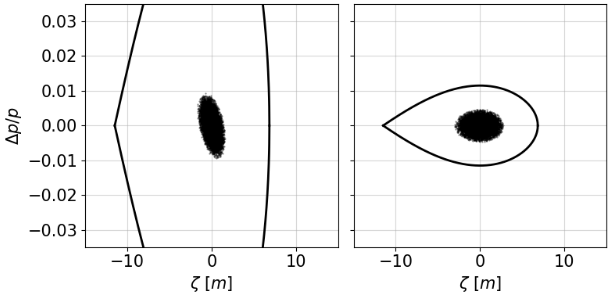

Figure 3: Longitudinal phase spaces $(\zeta, \Delta p/p)$ at $\gamma_0 = 6.08$. Left plot: crossing without γ_t-jump ($\gamma_{t,0} = 6.1$); right plot: crossing with γ_t-jump ($\gamma_{t,jump} = 6.58$).

The impact of the γ_t-jump scheme on the longitudinal phase space is presented in Fig. 3. In the reference case, at $\gamma_0 = 6.08$, the beam lies within the non-adiabatic region and exhibits the expected bunch-length shortening accompanied by an increase in momentum spread. In contrast, when the γ_t-jump is applied, the longitudinal motion at the same $\gamma_0 = 6.08$, remains adiabatic and the overall bunch-length reduction is minimized.

BENCHMARKING WITH MEASUREMENTS

By combining transition energy crossing with the γ_t-jump scheme, the model can be applied to operational beam conditions and benchmarked with measurements. For this purpose, the single-bunch nTOF beam was used as a reference case. In this configuration, transition crossing occurs at a cycle time of 381 ms. The time window 331–431 ms is sufficient to capture the relevant dynamics around this point. The machine and beam parameters at 331 ms are as follows:

Table 1: Machine and Beam Parameters for the nTOF Beam at Cycle-Time 331 ms (in Measurements and Simulations)

Machine and beam conditions at cycle-time 331 ms	
Energy γ_0	4.14
RF Voltage	200 kV
RF Harmonic	8
Intensity	8×10^{12} ppb
Emittance $\varepsilon_{x/y}$	13.5/8.5 μm
Bunch length σ_τ	80 ns

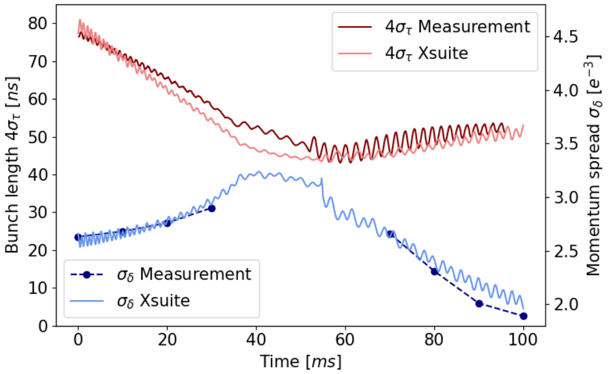

Figure 4: Bunch length and momentum deviation evolution during transition energy crossing (transition for $t \approx 50ms$), from measurements and Xsuite simulations (see parameters in Table 1).

The measured and simulated evolution of the bunch length and momentum spread are presented in Fig. 4. The effect of the γ_t-jump scheme is clearly visible in the bunch-length evolution, where the rapid shortening at transition is significantly reduced compared to Fig. 2. Overall, the simulations show good agreement with the measured longitudinal beam characteristics. Some discrepancies are nevertheless observed, particularly in the bunch length evolution. In the measurements the bunch shortening is less pronounced, while the post-transition oscillations are stronger than in simulations. These differences are likely attributable to collective effects, in particular longitudinal impedance and space-charge forces [7, 8].

COLLECTIVE EFFECTS

Collective effects constitute an essential component of the simulation model required for an accurate representation of the PS transition energy crossing. In this context, the influence of space charge and wakefields will be examined.

Effects of Space Charge

One of the most relevant collective effects during the CERN PS transition energy crossing is the direct space-charge force. This mechanism introduces an incoherent tune spread among the beam particles, and given its significant impact on the beam dynamics during transition crossing, it is explicitly included in the simulation model [9, 10].

Figure 5 shows the simulated space-charge induced tune-spread for two different energies, close to transition $\gamma_t = 6.1$.

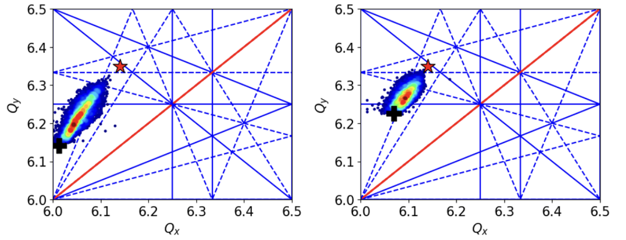

Figure 5: Tune diagram with simulated space-charge induced tune spread for $\gamma_0 \approx 4$ (left plot) and for $\gamma_0 \approx 7$ (right plot). The red stars indicate the set-tunes, and the black crosses the analytically predicted maximum tune shifts.

The simulation model incorporating direct space charge has already been employed in studies aimed at optimising the optics during transition-energy crossing. These studies contributed to a modified γ_t-jump scheme, scheduled for implementation during the next long shutdown of the PS, which will start on 2026 [11].

Effects of Wakefields

In addition to space-charge effects, wakefields play a significant role in high-intensity beams, as they can drive collective instabilities through beam–impedance interactions.

To account for these effects, the PS impedance model [12, 13] has been incorporated into the simulations of the transition energy crossing process. This model includes both dipolar and quadrupolar impedance contributions in the two transverse planes. For benchmarking purposes, the tracking simulations are compared against results from the semi-analytical Vlasov solver DELPHI [14–16], which computes complex coherent tune shifts induced by the beam coupling impedance.

At present, DELPHI does not support quadrupolar impedance contributions or nonlinear longitudinal dynamics. Therefore, for this comparison, the tracking simulations are restricted to dipolar impedance and a linear RF bucket model to ensure consistency between the two approaches.

Figure 6 shows the beam frequency spectrum obtained from tracking simulations [17], conducted at various beam intensities and an energy corresponding to $\gamma_0 \approx 5.44$. The respective tune shifts predicted by DELPHI are also overlaid.

Overall, good agreement is observed between the semi-analytical predictions and the tracking simulations in terms of mode evolution with increasing intensity. In particular, common structures such as the coupling of the -1 and -2 modes in the intensity range of approximately 0.5–1×10^{12}ppb are consistently reproduced. Larger discrepancies are observed for higher-order azimuthal modes, which may result from the limited number modes calculated with DELPHI.

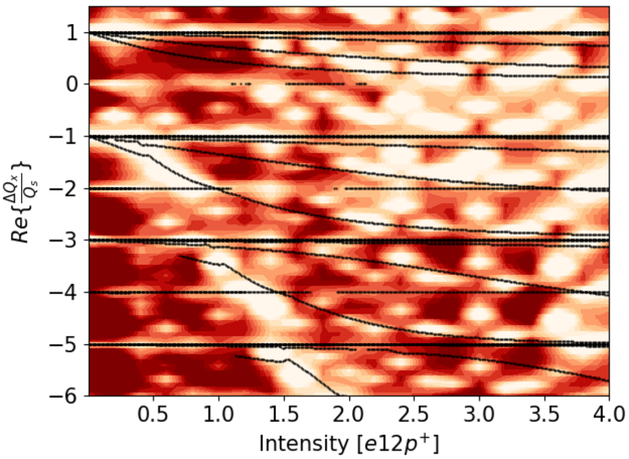

Figure 6: Normalised horizontal tune shift ($\Delta Q_x/Q_s$) along different intensities at $\gamma_0 \approx 5.44$. Q_s is the synchrotron tune at this time-stamp. The spectrum from the tracking simulations is shown along with the predictions from DELPHI.

CONCLUSION

Crossing of the transition energy constitutes a critical operational regime of the CERN Proton Synchrotron. To improve the understanding of its impact on beam dynamics, a dedicated tracking simulation model has been developed using the Xsuite framework.

As a first step, transition crossing was simulated and compared with analytical predictions. The model successfully reproduces the expected bunch-length shortening and momentum-spread increase during this phase.

Subsequently, the γ_t-jump scheme, which is employed operationally in the PS, was incorporated into the model. The combined transition-crossing and γ_t-jump model was benchmarked against measurements, showing good agreement in terms of bunch length and momentum-spread evolution.

Finally, collective effects, namely space charge and wakefields, were introduced separately. Wakefield effects were benchmarked against semi-analytical predictions obtained from the DELPHI Vlasov solver, showing consistent behavior. Work is ongoing for a complete description of transition energy crossing within the Xsuite framework, i.e. including both these effects together.

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