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HIGH INTENSITY EFFECTS OF FIXED TARGET BEAMS IN THE CERN INJECTOR COMPLEX

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Abstract

The current fixed target (FT) experiments at CERN are a complementary approach to the Large Hadron Collider (LHC) and play a crucial role in the investigation of fundamental questions in particle physics. Within the scope of the LHC Injectors Upgrade (LIU), aiming to improve the LHC beam production, the injector complex will be significantly upgraded during the second Long Shutdown (LS2). All non-LHC beams are expected to benefit from these upgrades. In this paper, we focus on the studies of the transverse instability in the Proton Synchrotron (PS), currently limiting the intensity of Time-Of-Flight (ToF) type beams, as well as the prediction of the impact of envisaged hardware modifications. A first discussion on the effect of space charge on the observed instability is also being presented.

INTRODUCTION

The LIU aims to increase the intensity and brightness of the LHC beams in the injector complex by about a factor of two in order to match the High Luminosity LHC (HL-LHC) requirements [1]. It will also maximize the injector reliability and lifetime to cover the HL-LHC era until around 2035. A new H^- Linear Accelerator (Linac4) [2] will be employed and major upgrades [3] in the PS Booster (PSB), the PS, and the Super Proton Synchrotron (SPS) are scheduled during the LS2.

Complementary to the high-energy colliders, a new exploratory study group, namely the Physics Beyond Colliders (PBC) [4] group, was officially formed in 2016 to explore the rich scientific potential of the CERN accelerator complex. This involves projects with a different approach to the LHC, HL-LHC and future colliders. The CERN injectors routinely provide non-LHC beams to facilities such as the ISOLDE Radioactive Ion Beam facility, the East Area (EA), the Antiproton Decelerator (AD) and Extra Low ENergy Antiproton (ELENA), the neutron Time-of-Flight facility (n-ToF), the High-Radiation to Materials (HiRadMat), the North Area (NA) and AWAKE.

The policy of the LIU for the non-LHC beams is at the minimum to preserve the present performance in terms of beam intensity and quality. In addition, a positive impact is expected thanks to the upgrades also for this kind of beams. Some of the facilities are in fact requiring or wishing a certain increase in the delivered proton beam intensity. In this paper, we will focus on the ongoing studies for the n-ToF, one of the FT experiments receiving protons from the PS.

Main Upgrades

The whole injector complex will undergo major upgrades during the LS2 to be able to fulfill the HL-LHC requirements. The upgrades in the PSB include the H^- charge exchange injection at 160 MeV instead of the 50 MeV proton injection of today, which will double the beam brightness out of the PSB. Due to a new radiofrequency (RF) system and an upgrade in the main power supply, the beam energy will also be increased from 1.4 GeV to 2 GeV. The 2 GeV extraction septum is already installed and used at 1.4 GeV until the LS2.

In the PS, the protons will be injected at 2 GeV allowing for brighter beams for the same tune shift. Moreover, a dedicated longitudinal feedback system will be used to mitigate the coupled-bunch instabilities and the longitudinal impedance of all the RF cavities in the PS will be reduced by about a factor of two [5] in order to be able to achieve the LIU baseline parameters.

In the SPS, reaching the LIU beam intensity requires a major upgrade of the main 200 MHz RF system in combination with an impedance reduction campaign. A new beam dump system will be placed in the long straight section LSS5 in order to cope with the higher beam intensities.

Regardless of these upgrades, it is necessary to study the future non-LHC beams by means of simulations and, whenever possible, measurements in order to ensure that the desired intensities are reached after the LS2.

ONGOING STUDIES

Future Beam Production in the PSB

The ISOLDE facility, receiving beam from the PSB, considers two operating scenarios after the LIU. The first is to maintain today's beam intensity of 0.8×10^{13} p per pulse per ring. The second is to double the intensity to 1.6×10^{13} p per pulse per ring while the number of cycles is reduced to avoid exceeding the limit of 2 μA of beam current, imposed by radiation protection (air activation). Space charge studies are ongoing to investigate the production of future high-intensity beams in the PSB.

A possible intensity limitation is a horizontal instability observed in the PSB above a certain intensity [6, 7]. Currently it is suppressed by the transverse damper, however, the origin of the instability remains unknown. The study of this horizontal instability is very important since after the LIU the injection energy will be 160 MeV, i.e. at exactly the energy that the instability appears for certain tune working points. Moreover, higher intensity beams are foreseen after the LS2 and the beams will be accelerated to a higher

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energy of 2 GeV, raising the question whether another critical energy exists for the beam stability. Simulations are ongoing [8].

High Intensity Beam for the NA

The NA receives today a proton beam from the SPS of about 3.5×10^{13} p/spill to fulfill the needs of the experiments. After LS2, an increased intensity of 4×10^{13} p/spill is assumed for future operation. Studies were realized to optimize the efficiency of the Multi-Turn Extraction (MTE) scheme in the PS. Following these efforts, a successful Machine Development showed that the desired intensity of 4×10^{13} p/spill could already be delivered [9], giving confidence that the post-LIU baseline intensity is within reach.

INSTABILITY AT TRANSITION IN THE PS

One of the facilities requiring higher beam intensity after the LIU is the n-ToF. Presently a pulse of around 7×10^{12} p is delivered from the PS to the n-ToF, while 1×10^{13} p per pulse would be the desired intensity in the future.

The PS regularly crosses transition energy and in order to maximize the delivered beam intensity, a second order γ jump scheme is used [10] to artificially increase the transition crossing speed by means of fast pulsed quadrupoles. Despite the fact that the intensity reach is considerably higher with the γ jump scheme active, i.e. it increases from $\sim 180 \times 10^{10}$ protons per bunch (ppb) to $\sim 800 \times 10^{10}$ ppb, one of the main intensity limitations is a fast vertical instability occurring near the transition energy above a certain intensity. Various experimental and simulation studies have been done in the past [11, 12]. The single-bunch instability has been characterized to be of Beam Break-Up (BBU) type due to the frozen synchrotron motion near transition crossing.

For the post-LIU operation, where higher beam intensities and brightnesses are required, it is crucial to identify the main sources of the instability and to propose mitigation techniques.

PS IMPEDANCE MODEL

The transverse PS impedance model has been already computed in earlier studies [13–16]. The main impedance sources such as the resistive-wall assuming a round chamber of 35 mm radius, the indirect space charge, the RF cavities, the kickers, the septum, the transition steps and the vacuum ports are included.

The total vertical PS impedance is plotted in Fig. 1. In dashed lines, the real and imaginary parts of the kickers' impedance are plotted. It can be seen that the real part of the total vertical impedance is dominated by the kickers' contribution up to ~0.9 GHz. The maximum in the real part of the kickers' impedance is found at ~0.7 GHz, the same frequency as the observed instability at transition, identifying the kickers as the main source of the instability [16]. However, reducing the kickers' vertical impedance is not foreseen within the LIU, making the mitigation studies crucial.

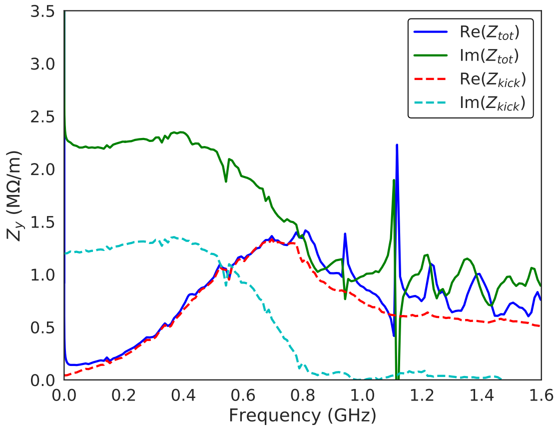


Figure 1: Vertical impedance model of the PS at 7 GeV.

SIMULATIONS WITH PYHEADTAIL

In order to study the fast single-bunch instability and investigate if its main characteristics can be reproduced with numerical simulations, the PyHEADTAIL 6D macroparticle tracking code [17] is used. The wake function is required as input to the code to simulate the effects of wakefields. An example of the transverse wake components, dipolar (dip) and quadrupolar (quad), at 7 GeV are shown in Fig. 2.

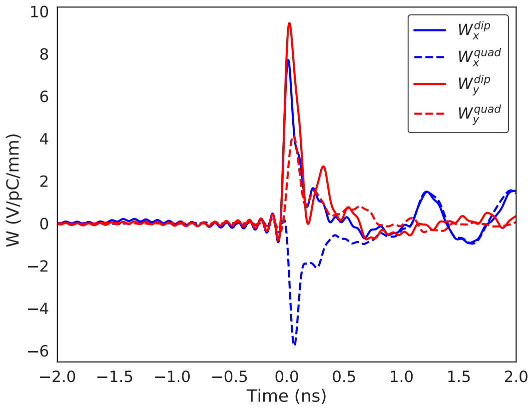


Figure 2: PS wake functions at 7 GeV.

Tune Shifts with Intensity

In the interest of benchmarking the developed PS impedance model, a set of PyHEADTAIL simulations was launched to compare the vertical tune shifts with intensity with the measured ones at different energies. The measured tune shifts at 2.0 GeV, 7.3 GeV, 13.1 GeV and 25.1 GeV were already taken during 2015 and presented in [16], with a chromaticity corrected as close to zero as possible. The comparison of the measured and simulated tune shifts is illustrated in Fig. 3 for the four energies.

At 2.0 GeV, 13.1 GeV and 25.1 GeV, an agreement of 85% to 90% is found between measurements and simulations. At the energy of 7.3 GeV, only 50% agreement is

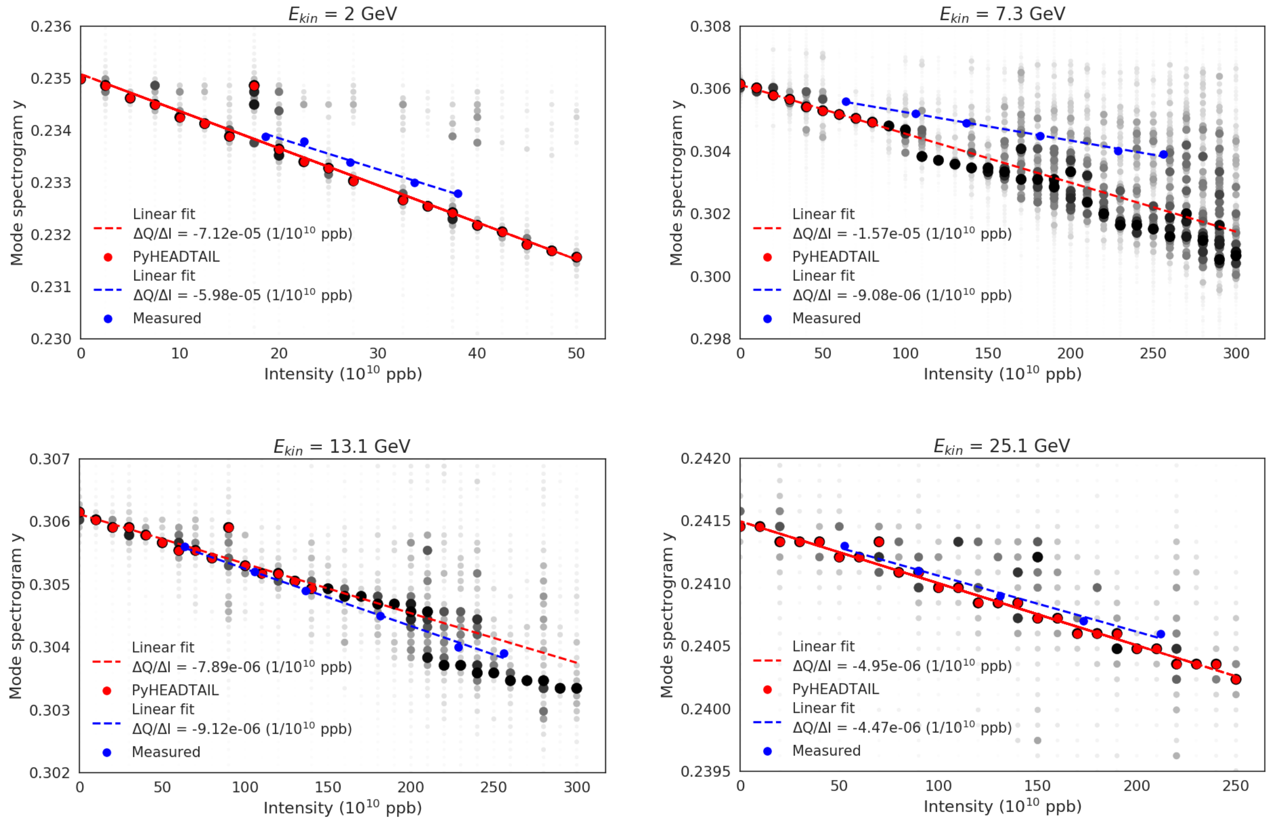


Figure 3: Comparison of measured and simulated tune shifts as a function of beam intensity for energies of 2.0 GeV, 7.3 GeV, 13.1 GeV and 25.1 GeV. Measured data are plotted in blue, simulated data in black and in red are the points used for the linear fit in PyHEADTAIL. An agreement of ~90% is found for all the energies apart from 7.3 GeV.

found. This is a very critical energy indeed, as it is near the transition crossing energy of 6.1 GeV. In the top right plot of Fig. 3, corresponding to the 7.3 GeV case, only the first simulated points marked with red color were used for the linear fit. The reason is that for intensities higher than 65×10^{10} ppb, the vertical centroid exhibits an exponential growth and becomes unstable. The measurements at this very critical energy are planned to be repeated this year before the LS2. Overall, a satisfactory agreement is found for most cases giving confidence that the imaginary part of the PS impedance is well modeled.

Frequency and Threshold of the Instability

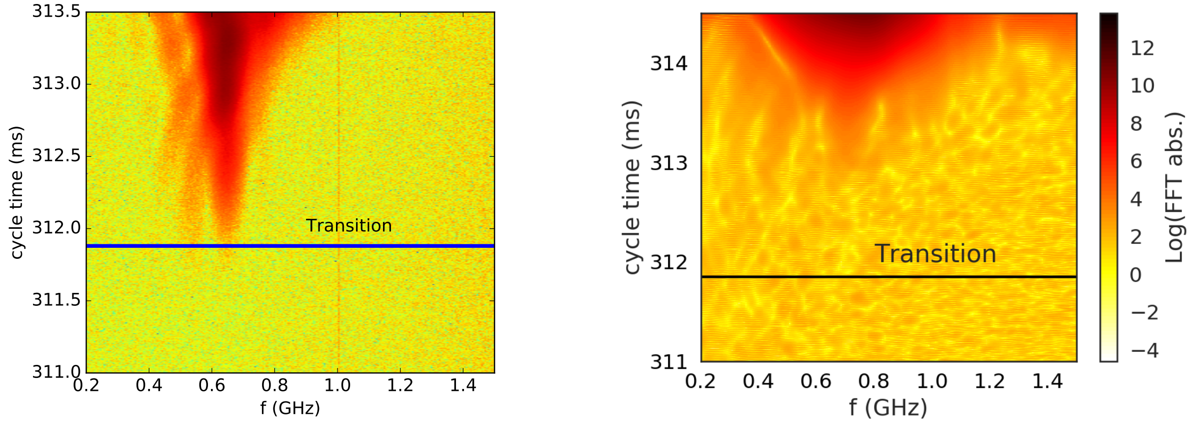
In order to identify the critical frequency of the instability, 35000 turns were tracked starting from a relativistic $\gamma = 4.0$ and accelerating the beam up to $\gamma = 7.4$, with a longitudinal emittance of $\varepsilon_z^{rms} = 0.44$ eVs, with zero chromaticity and assuming a Gaussian distribution. Transition occurs at $\gamma = 6.1$, thus allowing sufficient time for the instability to develop in PyHEADTAIL. The acceleration is included in the code by providing the measured change of the particle momenta as a function of γ. Figure 4 shows the comparison of the measured spectrogram with the simulated one. An FFT is performed on the centroid data to obtain the spectrogram. Measurements show the strongest part of the instability to be centered around 0.6 GHz to 0.7 GHz, in agreement with PyHEADTAIL. In addition, PyHEADTAIL also reproduces very well the onset of the instability in terms of cycle time in the PS with an error smaller than 0.5%.

An intensity scan is performed to identify the instability threshold predicted with PyHEADTAIL. With an emittance of $\varepsilon_z^{rms} = 0.44$ eVs and a transverse physical aperture of 35 mm radius included in the tracking code, the intensity threshold of $\sim 64 \times 10^{10}$ ppb is found. For this intensity, losses of the macroparticles on the vertical aperture are observed in Fig. 5. The predicted threshold is in fact a factor 2.5-3.0 lower than the measured value of $\sim 180 \times 10^{10}$ ppb, indicating that a stabilizing mechanism could be missing in the PyHEADTAIL simulations.

INCLUDING SPACE CHARGE IN PYHEADTAIL

A first hypothesis was that space charge could have an impact on the instability threshold. Up to now, any space charge induced tune spread was completely ignored.

A particle-in-cell (PIC) solver has been implemented in PyHEADTAIL and the simulations were also made available for graphics processing units (GPU) [19]. A 2.5D (i.e. slice-by-slice 2D transverse solving) Poisson solver was used with a 64 × 64 transverse mesh and 64 longitudinal slices. A smooth approximation was considered and 60 space charge



(a) Measurement (b) PyHEADTAIL

Figure 4: (a) Measured spectrogram with the instability being stronger around 0.6 GHz and 0.7 GHz [18]. (b) Simulated spectrogram with PyHEADTAIL, also indicating that the instability is centered around 0.7 GHz. The tracking code can also accurately reproduce the time in the PS cycle when the instability appears with an error less than 0.5%.

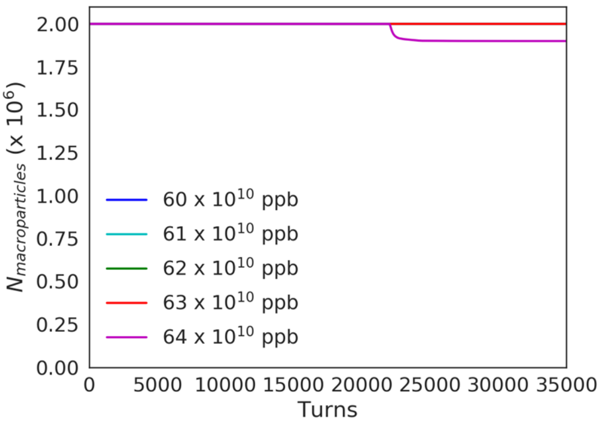


Figure 5: Number of macroparticles as a function of turns in PyHEADTAIL. Initial number of macroparticles is 2×10^6. Losses are observed near transition crossing for intensities higher than 64×10^{10} ppb.

kicks were applied along the machine circumference. A convergence study was done prior to the choice of these simulation settings.

Figure 6 shows in blue the measurements in the PS of the single bunch intensity threshold for different longitudinal emittances of a ToF-like beam without the γ jump scheme. A linear dependence is observed. In the same figure, PyHEADTAIL results are plotted in green (PyHDTL) accounting only for the effect of wakefields and neglecting any space charge effects. Although a linear dependence is also found in the simulation results, a significant discrepancy with the measurements can be noted, up to almost a factor 3. In the same figure and in red color, the PyHEADTAIL results including the 2.5D PIC space charge module are shown. The simulations indicate that including space charge effects in the macroparticle tracking model is important and helps approach the measured values. However, there is still some discrepancy and further studies are ongoing.

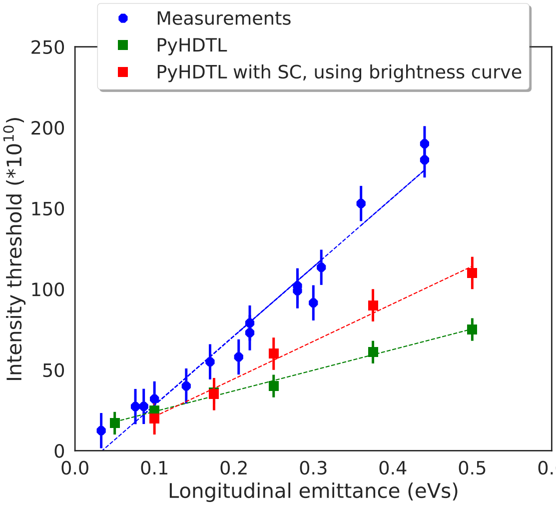


Figure 6: Single bunch intensity thresholds as a function of the longitudinal rms emittance for a ToF-like beam without the γ jump.

An important input for the space charge simulations are the values of the transverse emittances for each longitudinal emittance. At present, the simulated emittance values are assumed to follow the PSB measured brightness curve [20], thus they are intensity dependent. The brightness of the LHC-type beams is determined by the efficiency of the multi-turn injection in the PSB as well as the space charge effects during the injection process. The n-ToF beam follows the same brightness curve, as it was found from measurements, which gave a slope value of ~0.011 (μm/10^{10}p). As a first approximation, the horizontal and vertical emittances were assumed to be equal and the values in Table 1 were used in the PyHEADTAIL simulations.

Table 1: Transverse emittances for each longitudinal emittance, following the measured brightness curve.

ε_z^{rms} (eVs)	$\varepsilon_{x,y}$ (µm)
0.10	0.3
0.18	0.6
0.25	1.0
0.38	1.5
0.50	2.1

As a next step, more realistic values of the transverse emittances will be used, given the fact that the horizontal emittance is usually larger than the vertical one for the n-ToF beam. For this purpose, the measurements will be repeated and the values of the transverse emittances will be closely monitored.

REMOVAL OF OBSOLETE EQUIPMENT

Obsolete equipment that used to be part of the Continuous Transfer (CT) extraction scheme [21] in the PS was decided to be removed during the LS2. This includes, among other components, the electrostatic septum and kickers used for the generation of the five-turn extraction bump. The aforementioned components were removed from the PS impedance model and a new wake function that does not include the CT equipment was introduced in PyHEADTAIL. The difference in the vertical wake function before and after removing the CT equipment can be seen in Fig. 7.

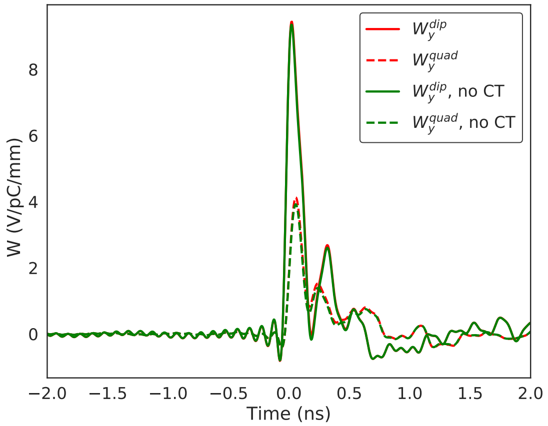


Figure 7: Wake functions with and without the CT equipment. The difference between the two is very small.

Although as a general rule, removing equipment can decrease the impedance of an accelerator, simulations showed that the particular components of the CT extraction do not largely contribute to the total machine impedance. The negligible effect of the envisaged hardware modification was further verified by obtaining the same threshold of 64×10^{10} ppb with PyHEADTAIL, as in the case where the total PS wake field is used. The prediction will be cross-checked with beam-based measurements after the LS2, however, no significant benefit is expected for the instability threshold.

CONCLUSION

Apart from the LHC-type beams, some FT experiments would certainly benefit from higher intensity and brightness beams that will be available thanks to the LIU.

In particular, the ISOLDE facility could accept a double intensity of $1.6{\times}10^{13}$p per pulse per ring after LS2. Ongoing studies will address the question of the full extent of the intensity reach depending on the Linac4 parameters.

Other non-LHC users, such as the n-ToF would desire higher beam intensity after LS2 but current intensity limitations need to be addressed. Progress has been made in the understanding of the fast vertical instability mechanism as well as the influence of space charge on the predicted thresholds. Simulations with PyHEADTAIL indicate that the envisaged removal of the CT equipment will not alter significantly the machine impedance and thus the instability threshold. Other mitigation techniques, such as the optimization of the γ jump scheme, the chromaticity along the cycle and the use of octupoles, are under investigation.

Concerning the NA beam intensity request after the LS2, a successful machine test in 2017 proved that the desired intensity of 4×10^{13} p/spill can already be reached.

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