SUPPRESSION OF HALF-INTEGER RESONANCE IN FERMILAB BOOSTER*

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Abstract

The particle losses at injection in the FNAL Booster are one of the major factors limiting the machine performance. The losses are caused by motion nonlinearity due to direct space charge and due to nonlinearity introduced by large values of chromaticity sextupoles required to suppress transverse instabilities. The report aims to address the former - the suppression of incoherent space charge effects by reducing deviations from the perfect periodicity of linear optics functions. It should be achieved by high accuracy optics measurements with subsequent optics correction and by removing known sources of optics perturbations. The study shows significant impact of optics correction on the half-integer stop band with subsequent reduction of particle loss. We use realistic Booster lattice model to understand the present limitations, and investigate the possible improvements which would allow high intensity operation with PIP-II parameters.

INTRODUCTION

The Booster has been the workhorse of the Fermilab accelerator complex for several decades and continues to deliver high-intensity high-repetition rate proton beams for the physics program. Recent improvements allowed to obtain beam acceleration at each Booster cycle. It increased the effective ramp rate from 7 to 15 Hz and played a significant role in attaining the 700 kW operation for NOvA experiment [1]. The Booster intensity is limited by particle losses throughout the injection, acceleration, and extraction cycle, which lead to the radio-activation of the accelerator components and enclosure. Consequently, the examination of the loss sources and development of ways to mitigate them are the continued focus of efforts. It becomes especially important in view of the upgrade plans for the PIP-II project [2]. The area of interest for the present report is the particle losses induced by direct space charge interaction at injection energy.

The studies of space charge effect in FNAL Booster have a long history. A massive campaign to simulate and mitigate the losses at injection was undertaken during the Tevatron collider Run II [3-7]. In particular, it was determined that the extraction dogleg that disturbs the 24-fold lattice symmetry of the Booster and thus enhances the half-integer stop band can have a significant impact on the single-particle dynamics [4]. The importance of half-integer resonance has been realized by Sacherer [8] and later research confirmed and enhanced the aspects of interplay between space-charge and lattice resonances [9-13]. Also, significant progress has been made in the accurate measurement and reconstruction of the Booster optics model owing to the implementation of the LOCO algorithm [13]. This makes it possible to model the beam dynamics with the actual machine configuration in operations and then perform predictable adjustments.

The present work aims at i) revisiting the space-charge dynamics in the FNAL Booster making use of the recent improvements in the lattice model and understanding the main limiting factors; ii) proposing operational improvements to reduce particle losses; iii) making projections towards operation with PIP-II parameters or even higher intensity.

APPROACH AND TOOLS

In the present study we concentrate solely on the incoherent single-particle effects arising through the time-modulation of nonlinear transverse self-field within the bunch and the betatron and synchro-betatron resonances leading to the beam emittance growth and particle losses. We also limit the time period of interest to a few hundred turns right after the beam injection and bunching and before the energy ramp. Such approach allows to use relatively simple tools for the modelling of space-charge effects – the so-called frozen space-charge model that implies Gaussian beam density profile. We also approximate the smooth azimuthal distribution of space-charge action by a number of thin kicks along the orbit. The advantage of such approach is the fast calculation time and the availability of reasonable well developed and tested tracking codes. In the future the simulations will be augmented by the true self-consistent PIC tools.

We use the simplified and realistic Booster lattice models [13] to quantify the requirements on optics control that would help mitigating particle losses at injection. The simplified representation is a 24-cell symmetric lattice with some artificially introduced gradient errors, which emulate the beta-beating of the realistic lattice.

The code used in this study was Lifetrac [14], a particle tracking code developed for modelling beam-beam interactions. The machine lattice was modelled using the element-by-element drift-kick approximation. The lattice data are imported from MAD-X [15] model files where the element slicing is performed using the methods available internally in MAD-X. For the purpose of this work the slicing was done with the so-called Teapot algorithm [16]. The thin lens tracking is implemented following [17], and makes use of the paraxial approximation for the multipole elements and properly treats non-paraxial effects in the drifts. This method proved to be accurate for the LHC and DAΦNE tracking studies [18].

We used 120 thin beam-beam elements (17 per betatron period) to model the action of space-charge. The simplifications limiting the physics model in the study were: i)

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non-adaptive space-charge algorithm (i.e. the beam emittance was considered frozen) and ii) no modulation of space-charge kick by the longitudinal particle position within the bunch (which overestimates the space-charge effect but neglects synchro-betatron resonances).

The beam parameters used in the studies for the present Booster operation and for the PIP-II scenario are listed in Tables 1 and 2, respectively. The lattice functions of the idealized 24-period model and the actual reconstructed Booster model are shown in Figs. 1 and 2.

Table 1: Booster Nominal Parameters in Simulation

Beam energy	400 MeV (β=0.713, γ=1.426)
RF Voltage	0.7 MV
Synchrotron tune	0.078 (35 kHz)
Bucket size	4.2×10^{-3}
Energy spread	2.1×10^{-3}
Bunch length	σ_z=1.26 m
Transverse emittance	15 mm×mrad (95% normalized)
Aperture	2.86 cm in H, 2.08 cm in V
Betatron tunes	Q_x=6.70, Q_y=6.80
Chromaticity	C_x=-20, C_y=-14
Number of particles	0.42×10^{13} in 84 bunches
Space-charge tune shift	ΔQ_x=-0.197, ΔQ_y=-0.307

Table 2: Beam Parameters for PIP-II scenario

Number of particles	0.66×10^{13} in 84 bunches
Space-charge tune shift	ΔQ_x=-0.31, ΔQ_y=-0.4

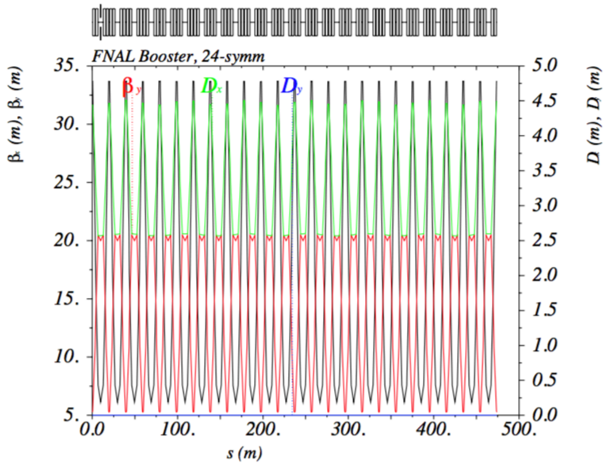

Figure 1: Lattice functions of idealized 24-period model.

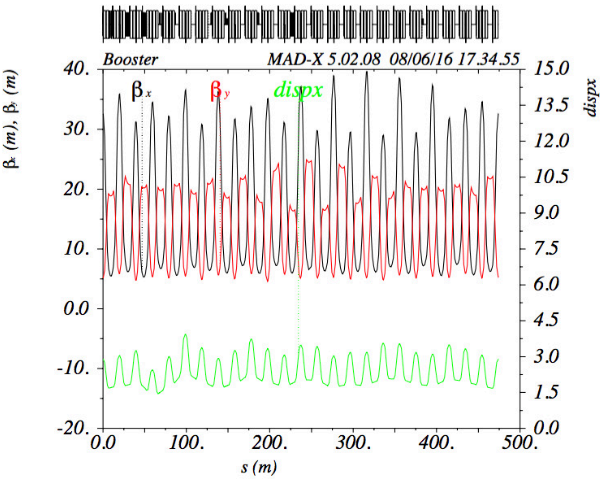

Figure 2: Lattice functions of LOCO measured model.

RESULTS AND DISCUSSION

We perform macro-particle bunch simulations to evaluate the evolution of beam emittance and particle losses. Figures 3-5 show the beam intensity and emittance over 10,000 tracking turns for the nominal and PIP-II scenarios. It is clear that for the PIP-II parameters even a minor distortion of the ideal 24-fold symmetry leads to significant losses. One should remember, however, that the employed model overestimates the space-charge effect and the final conclusions could be less restrictive.

We also rely on the Frequency Map Analysis [19] for better understanding of the beam dynamics. Figures 6-17 present the frequency maps for the three cases of lattice (ideal 24-fold symmetry, 10% beta-beat, and 20% beta-beat) for two values of the beam intensity – nominal and PIP-II. The color in plots represents the betatron tune variation along the particle trajectory over 1000 turns (blue – 10^{-7}, red – 10^{-3}). The axes in the amplitude space are labelled in units of beam sigma.

One observes that in the ideal 24-periodic lattice the half-integer stop band is not present and the dynamics is well-behaved. The particle losses can probably be attributed to the action of nonlinear coupling resonance $2Q_x$-$2Q_y$=n. As the perfect periodicity is ruined, the width of ½ resonance increases and it also starts to overlap with the coupling resonance, considerably shrinking the stable motion area.

The dynamics of particles with energy offset (not shown) exhibits a more pronounced effect of the half-integer resonance due to the impact of chromaticity. However, in the present model the transverse space-charge kick was not modulated by the longitudinal position in the bunch and drawing conclusions from the off-momentum particle results would be premature.

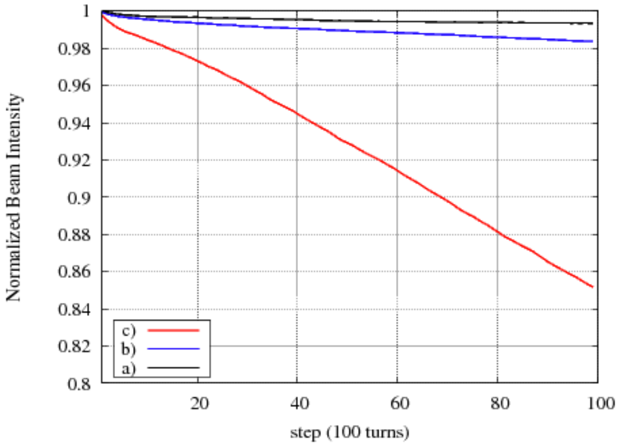

Figure 3: Simulated evolution of normalized bunch intensity over 10,000 turns for the nominal Booster parameters. a) idealized 24-period lattice; b) 10% beta-beat lattice; c) 20% beta-beat lattice.

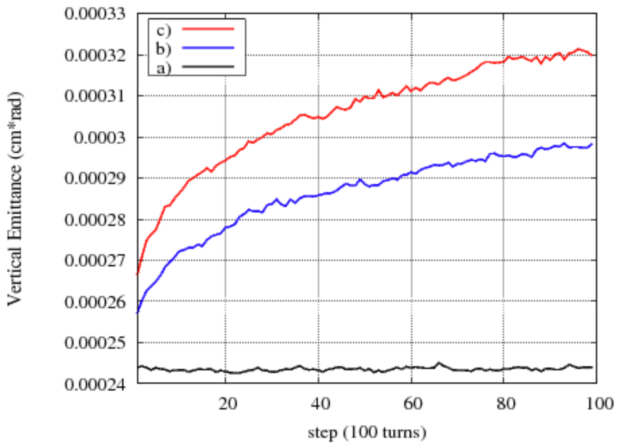

Figure 4: Simulated evolution of beam emittance over 10, 000 turns for the nominal Booster parameters. a) idealized 24-period lattice; b) 10% beta-beat lattice; c) 20% beta-beat lattice.

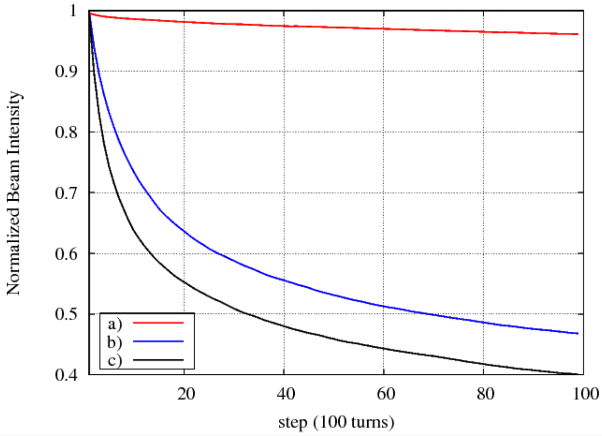

Figure 5: Simulated evolution of normalized bunch intensity over 10,000 turns for the PIP-II scenario parameters. a) idealized 24-period lattice; b) 10% beta-beat lattice; c) 20% beta-beat lattice.

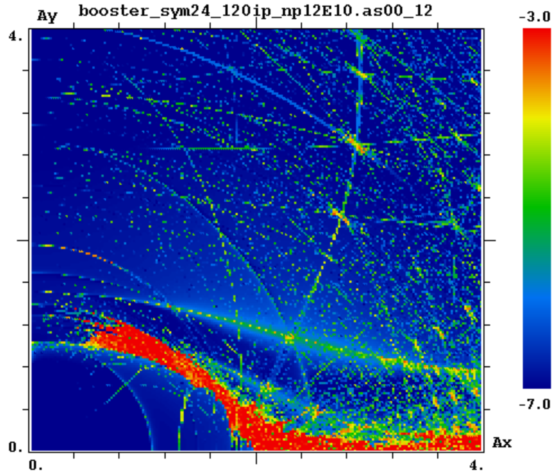

Figure 6: FMA in the amplitude space for the nominal parameters in idealized 24-period lattice.

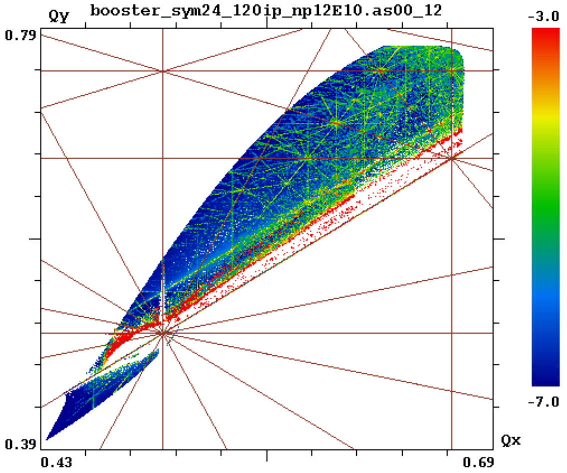

Figure 7: FMA in the tune space for the nominal parameters in idealized 24-period lattice.

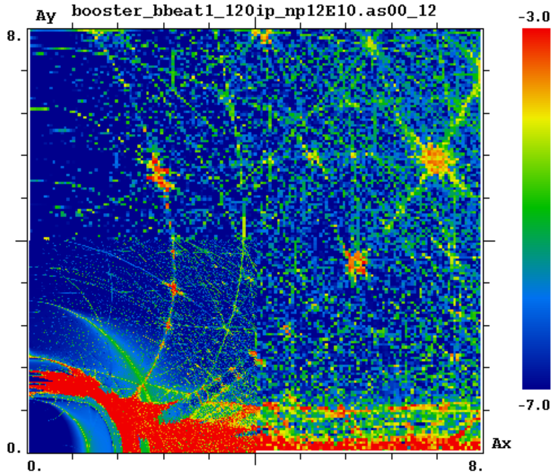

Figure 8: FMA in the amplitude space for the nominal parameters in 10% beta-beat lattice.

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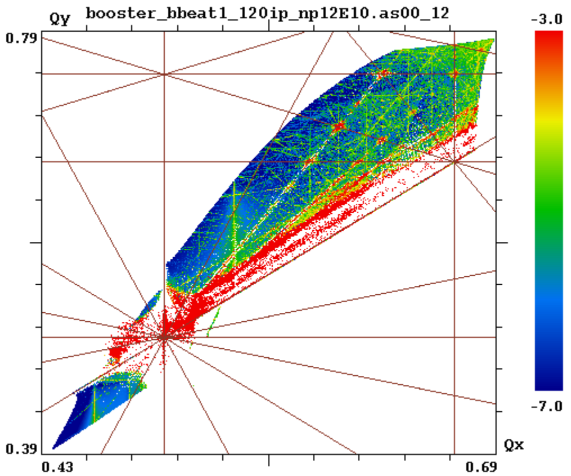

Figure 9: FMA in the amplitude tune space for the nominal parameters in 10% beta-beat lattice.

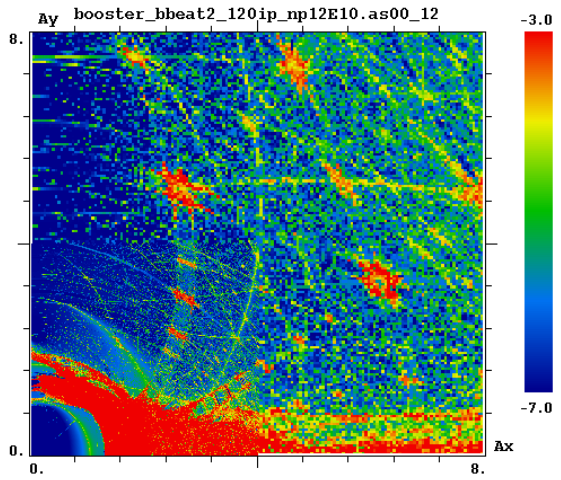

Figure 10: FMA in the amplitude space for the nominal parameters in 20% beta-beat lattice.

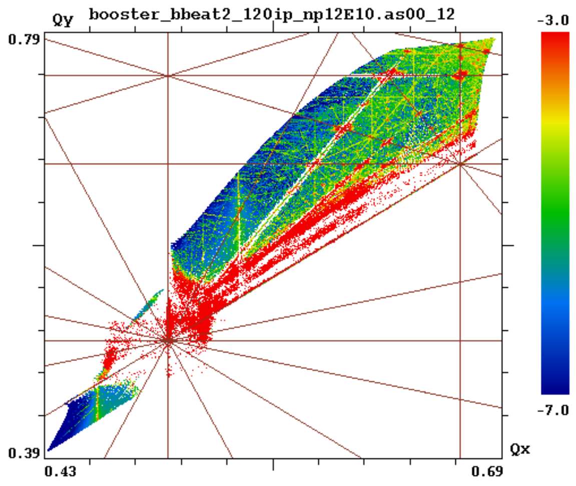

Figure 11: FMA in the tune space for the nominal parameters in 20% beta-beat lattice.

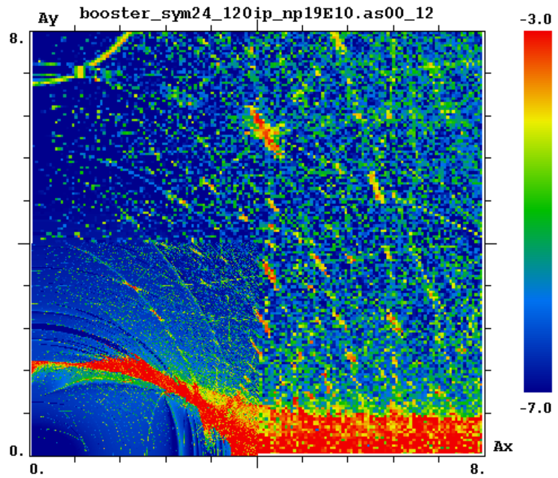

Figure 12: FMA in the amplitude space for the PIP-II scenario parameters in idealized 24-period lattice.

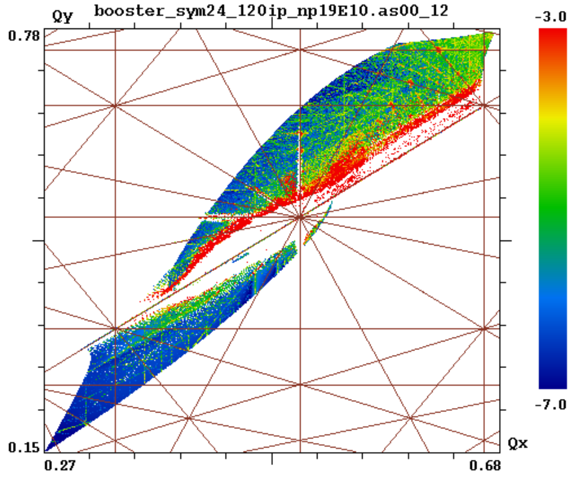

Figure 13: FMA in the tune space for the PIP-II scenario parameters in idealized 24-period lattice.

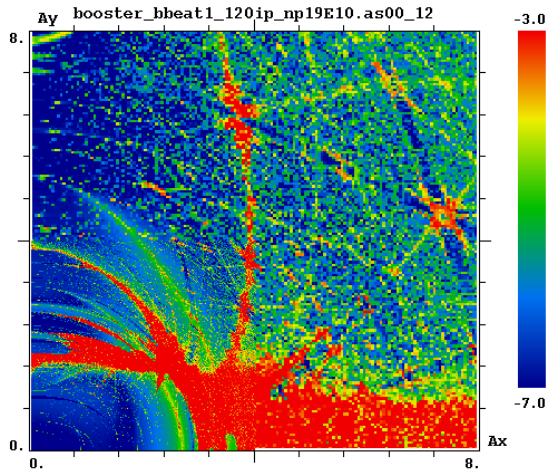

Figure 14: FMA in the amplitude space for the PIP-II scenario parameters in 10% beta-beat lattice.

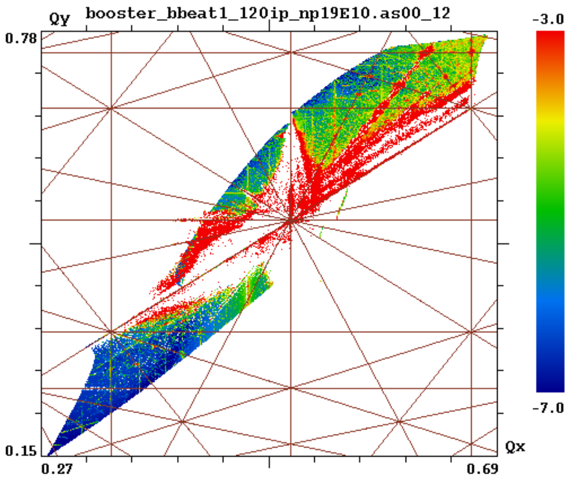

Figure 15: FMA in the tune space for the PIP-II scenario parameters in 10% beta-beat lattice.

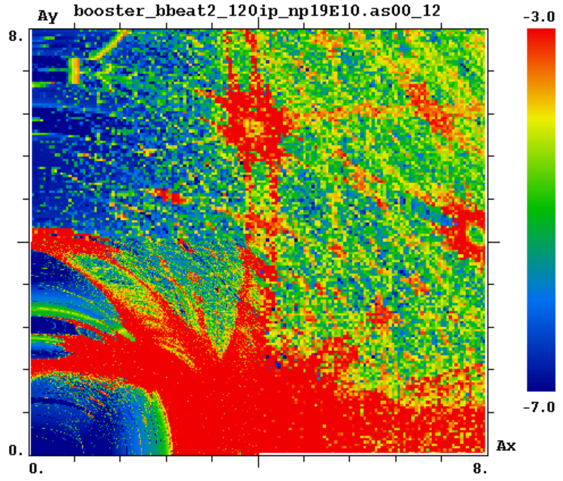

Figure 16: FMA in the amplitude space for the PIP-II scenario parameters in 20% beta-beat lattice.

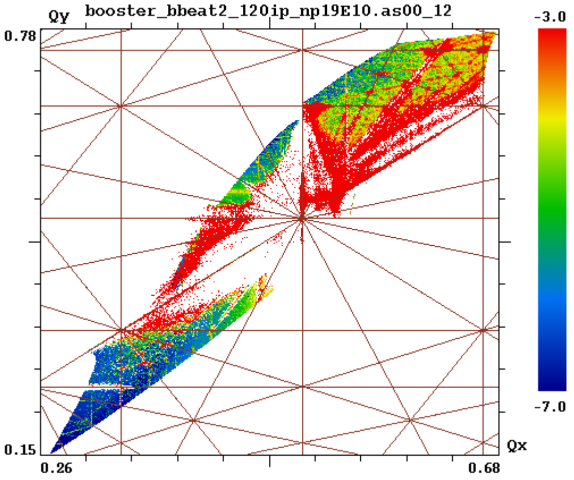

Figure 17: FMA in the tune space for the PIP-II scenario parameters in 20% beta-beat lattice.

SUMMARY

The employed model allows for very fast evaluation of machine tuning options with known limitations (non-adaptive space-charge and the absence of synchrotron modulation). The implementation of these features in Lifetrac is in progress. In parallel, the MAD-X space-charge module is being tested on the test cases discussed in this report.

The preliminary results indicate the importance of the half-integer resonance as a limiting factor: at the beam intensities exceeding 0.4×10^{13} the core particles cross the half-integer line, also the perfectly symmetrical 24-period lattice allows for operation with the intensity of 0.66×10^{13}.

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