NUMERICAL SIMULATIONS OF COLLIMATION EFFICIENCY FOR BEAM COLLIMATION SYSTEM IN THE FERMILAB BOOSTER*

V.V. Kapin#, V.A. Lebedev, N.V. Mokhov, S.I Striganov, I.S. Tropin,
Fermilab, Batavia, IL 60510, USA

Abstract

A two-stage beam collimation (2SC) system has been installed in the Fermilab Booster more than 10 years ago. It consists of two primary collimators (horizontal and vertical) and three 1.2m-long secondary collimators. The two-stage collimation has never been used in Booster operations due to uncontrolled beam orbit variations produced by radial cogging (it is required for beam accumulation in Recycler). Instead, only secondary collimators were used in the single-stage collimation (1SC). Recently introduced magnetic cogging resulted in orbit stabilization in the course of almost entire accelerating cycle and created a possibility for the 2SC. In this paper, the 2SC performance is evaluated and compared the 1SC. Several parameters characterizing collimation efficiency are calculated in order to compare both schemes. A combination of the MADX and MARS15 codes is used for proton tracking in the Booster with their scattering in collimators being accounted. The dependence of efficiency on the primary collimators foil thickness is presented. The efficiency dependence on the proton energy is also obtained for the optimal foil. The feasibility of the 2SC scheme for the Booster is discussed.

INTRODUCTION

The Fermilab Booster [1] is a 15Hz rapid cycling synchrotron accelerating protons from 400 MeV to 8 GeV with accelerating efficiency about 90%. Booster optics is based on combined function dipoles and includes 24 equal-length periods. Totally, about 10% of protons are lost during 20,000-turn accelerating cycle. Major fraction of loss happens at the beginning of the accelerating cycle.

The Proton Improvement Plan (PIP) [2] established in 2012 is aimed to double the beam throughput, while maintaining the present residual activation levels. One of many other PIP tasks is a possible upgrade of the Booster collimation system installed in 2004. It is located in the periods 5, 6 and 7.

The booster collimation system has been designed as a two-stage collimation (2SC) system. However, this design was not compatible with uncontrolled radial orbit variations inherent to the radial cogging used in Booster till 2015. Therefore, the collimation system was used in a single stage (1SC) mode, which was still ensuring a significant reduction in Booster activation.

Implementation of new magnetic cogging in 2015 [3] resulted in a stable beam orbit and created conditions for implementation of the 2SC aimed to reduce uncontrolled beam losses mostly generated shortly after injection. In this paper, the collimation efficiency of the 2SC in the vertical plane is evaluated and compared with that of the existing 1SC.

BOOSTER COLLIMATION SYSTEM

Each Booster period contains two horizontally focusing (F) and two horizontally defocusing magnets (D) separated by two straight lines (6.0-meter "long straight " and a 1.2-meter "short straight") and two 0.5-meter short drifts separating F and D magnets. The 2SC system has been installed in the straight sections of periods 5, 6, and 7. Figure 1 shows layout of the 2SC system. It consists of horizontal (H-prim) and vertical (V-prim) primary collimators located in the short drifts nearby of Short-5 and three identical 1.2 m-long secondary collimators (or absorbers) 6A, 6B, and 7A located in Long-6 and Long-7. Each absorber is capable to limit aperture in both planes.

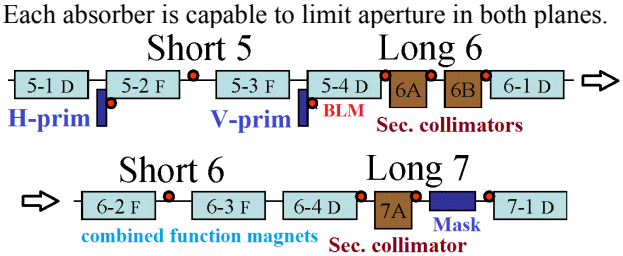

Figure 1: Layout of 2SC system in periods 5, 6 and 7.

The primary collimators are movable thin scattering foils. The absorbers are movable girders with square cross-section with square apertures in the center for beam passage. The 2004 original 2SC design [4,5] considered the beam core to be equal 3σ for normalized 95%-emittances of 12π mm·mrad. For collimation in the vertical plane, collimators V-prim, 6A and 7A are used. V-prim is placed at the lower edge of the 3σ-beam core. The jaws of the 6B and 7A collimators are positioned with a 2mm offset from the 3σ-beam core, while the jaw of collimator 6B is located below the beam and the jaw of collimator 7A is located above the beam.

The purpose of this 2SC is to localize proton losses inside the secondary collimators, so that to reduce irradiation of the rest of the machine to an acceptable level.

SIMULATION APPROACH

The 2004 original 2SC had been designed with the STRUCT code [6], which simulated a multi-turn tracking of halo protons in the Booster lattice with their scattering on collimators. Protons lost on the machine components were stored to the files for the next step of calculations with the MARS code [7], which performed full-scale

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
# kapin@fnal.gov

Monte Carlo hadronic and electromagnetic shower simulations.

The original model of the 2SC studied with STRUCT [4] had twice-shorter 0.6 m-long secondary collimators, while MARS simulation [4] has been done for the finally-installed 1.2 m-long secondary collimators. Since the STRUCT code is not presently maintained at Fermilab, it has been decided to replace it by tracking with MADX [8], which has been adapted for simulations of the 2SC. A combination of the MADX and MARS15 codes is used for proton tracking in the Booster with their scattering on collimators.

Adaptation of the MADX code included modifications of both a MADX script for the Booster lattice and a MADX source code itself. The apertures for all Booster elements have been inserted into the MADX-lattice using sizes given either in the STRUCT-lattice file or in the engineering drawings. Also, a new trapezoidal aperture for the Booster combined function magnets has been implemented in the MADX source code.

The proton out-scattering in absorbers is simulated via a direct use of the MARS code. In order to simulate proton interaction with the thin foils of the primary collimators, the TARGB module of the STRUCT code has been transferred to the MADX code. The TARGB code is based on an old version of the MARS code. It uses the Monte-Carlo simulations of physical processes causing energy loss and scattering of protons in thin primary collimators. The multiple Coulomb scattering is simulated with the Moliere distribution. The Landau distribution is used for computation of energy loss.

The simulation algorithm includes the following steps:

a) generation of halo proton distribution near the edge of a primary collimator with an external script;
b) multi-turn tracking of halo protons using the MADX thin-track module including proton interactions with foils of primary collimators (via TARGB) and recording coordinates of protons lost on lattice apertures;
c) collection of protons lost on apertures of each absorber and restoration of their coordinates at the front planes of the absorbers using an external script;
d) tracking protons collected at the previous step through each absorber using its MARS models;
e) collection of protons out-scattered from absorbers at the back plane of absorbers using an external script;
f) tracking of out-scattered protons from the back plane of absorbers using MADX and recording lost protons;
g) post-processing via counting lost protons on lattice elements before and after tracking with MARS code, *i.e.* with or without out-scattering effects.

ABSORBER MODEL IN MARS CODE

In order to simulate correctly out-scattering of protons in absorbers, a MARS model has been created for 3 identical secondary collimators. The model is used by MADX as a "black-box", while real transverse shifts of absorbers are simulated via virtual shifts of proton coordinates.

The MARS model has been also used for calculation of the absorption efficiency of a single absorber allowing us to evaluate an efficiency of the 1SC system. It is known that there is a strong dependence of the absorption efficiency on angular alignment of the absorber jaw and size of the beam halo [9]. Figure 2 shows a longitudinal section of the absorber having a frontally-tapered square aperture and positions of incident halo rays used in the simulations. The halo rays with negative slopes $x'<0$ cross the absorber jaw at its tapered front end while the halo rays with $x'>0$ cross the jaw at its rectangular back end.

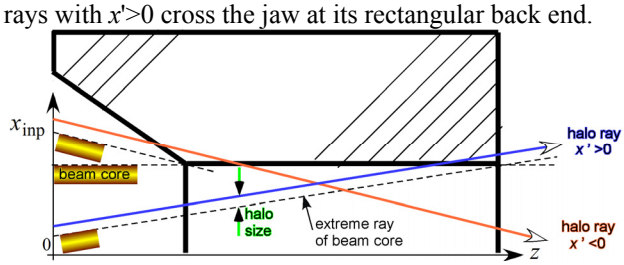

Figure 2: Longitudinal section of absorber and positions of halo rays at $x' > 0$ (blue) and $x' < 0$ (red).

In simulations, the halo rays consist of $N_{halo}=10^4$ protons with identical input coordinates (x_{inp}, x'), while x_{inp} is explicitly defined by x' due to an assumption that the beam core just touches absorber surface. Counting the number of protons lost in absorber N_{lost}, the absorption efficiency is defined as $\varepsilon_{abs}=N_{lost}/N_{halo}$. Figure 3 shows ε_{abs} versus the beam slope x' at different halo sizes for 400 MeV protons.

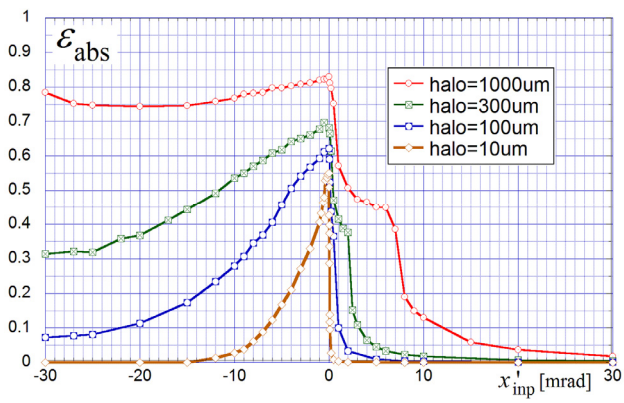

Figure 3: ε_{abs} *vs* beam slope x' at different halo sizes: 10μm (brown), 100μm (blue), 300μm (green), 1mm (red).

The ε_{abs}-curves have maximum values at zero x', *i.e.* at an ideal angular alignment. The maximum values depend on the halo size and reach 55%, 62%, 68%, and 83% for the halo sizes of 10μm, 100μm, 300μm, and 1mm, respectively. The efficiency ε_{abs} for halo rays with negative slopes ($x'<0$) is considerably higher than for rays with positive slopes ($x'>0$) since the frontally-tapered aperture increases the effective absorption length for halo rays with $x'<0$ in comparison to halo rays with $x'>0$, which cross a relatively sharp non-tapered back end of the jaw. Unfortunately, the absence of tapering for the back end jaws of the Booster absorbers fabricated in ~2003 reduces a range of x' with a high ε_{abs} by a factor ~2.

SIMULATIONS FOR 2SC SYSTEM

The Booster is an accelerator with rapidly variable parameters. This implies many difficulties for its 2SC system in comparison with fixed-energy storage rings. For example, the beam center positions and beam sizes are considerably changed during acceleration. Collimators are passive devices with fixed geometry and positions, while scattering angles at foils decrease with energy. Therefore, an effective collimation for the 2SC system can only be done within a narrow energy range and during a limited number of beam turns. Presently, the 2SC system is aimed to control beam losses at 400MeV.

According to the 2004 design [4], the primary collimators should use a 0.15mm graphite foil at 400 MeV, which is equivalent to ~0.012mm copper foil. During past years, different foils had been tested. Most recently, the 0.381mm copper foil has been installed. Obviously, it produces much larger angular kick at 400MeV than the original design foil.

Among other things, present simulations with the 2SC system are to define an optimal foil thickness t_{PrColl} at 400 MeV. Here, results for 2SC in the vertical plane with copper foils are presented. It is assumed that all the collimators are positioned according to the 2004 design [4]. The simulations have been done using the bundle of MADX and MARS15 codes for halo protons, $N_{halo}=10^4$, distributed along the front edge of the vertical primary collimator.

Figure 4 shows the total number of protons lost around the ring N_{lost} versus t_{PrColl}. The simulations take into account the out-scattering effect in absorbers and only absorbed protons $N_{SecColl}$ are included into N_{lost}. Figure 5 shows dependence of $N_{SecColl}$ on t_{PrColl}. The 10-turn curve has a maximum at t_{PrColl}~90μm, and the 100-turn curve has a maximum at t_{PrColl}~30μm.

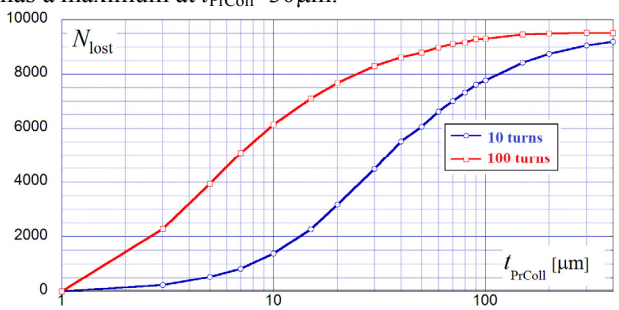

Figure 4: N_{lost} *vs* t_{PrColl} after 10 (blue) and 100 (red) turns.

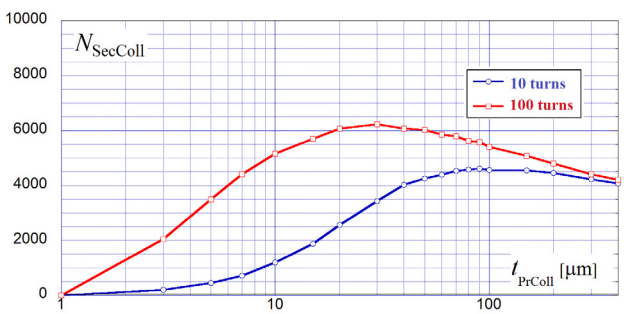

Figure 5: $N_{SecColl}$ *vs* t_{PrColl} after 10 and 100 turns.

The collimation efficiency can be defined either as $\varepsilon_{halo}= N_{SecColl}/N_{halo}$ [10-12] or as $\varepsilon_{lost}= N_{SecColl}/N_{lost}$ [9,10]. Both efficiencies become the same when all halo protons are lost ($N_{lost}=N_{halo}$). Figure 6 shows both collimation efficiencies as a function of the foil thickness t_{PrColl}. The ε_{lost}-curves at 10 and 100 are overlapped, i.e. ε_{lost} does not depend on number of turns if it > 10. ε_{lost} have maximum values ε_{lost}~90% at t_{PrColl}<10 μm. However, less than a half of halo protons are lost on absorbers after 100turns (see Fig.5), and the efficiency ε_{halo}<50% at t_{PrColl}<10 μm.

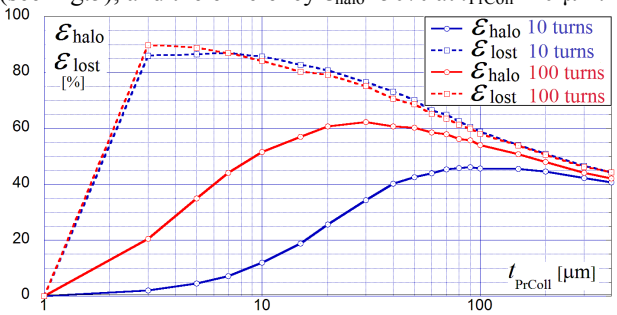

Figure 6: ε_{halo} and ε_{lost} *vs* t_{PrColl} after 10 and 100 turns.

Our simulation model assumes non-variable parameters of a Booster like storage ring. On the other hand, trajectories of scattered halo particles in the Booster can be essentially distorted due to variations of beam energy and central orbit, and other fluctuating parameters. It is not known how many turns can be considered as "frozen".

Let's assume that several tens of turns have "frozen" conditions. The optimal thickness of Cu foil for several tens of turns is around 50 μm. To ensure the mechanical rigidity of the primary foils construction, an equivalent Al foil with thickness of 380 μm has been installed [13].

Figure 7 shows both the collimation efficiencies as a function of beam kinetic energy W_{kin} for the installed foil. The ε_{halo}-curves have a maximum values near 400MeV, while ε_{lost}-curves show a quite high "optimistic" values.

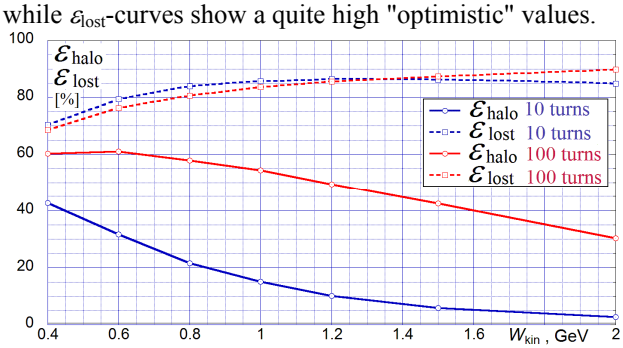

Figure 7: ε_{halo} and ε_{lost} vs W_{kin} after 10 and 100 turns.

CONCLUSIONS

Presented results suggest:

a) if "frozen" conditions in the Booster exist for more than 100 turns, then the efficiency of 2SC, ε_{halo}>60%;
b) if the beam halo size ≤10μm, the absorption efficiency of 1SC, ε_{abs}<55%;
c) Under the above conditions the 2SC system could be more effective than the 1SC system.

REFERENCES

[1] E.L. Hubbard *et al.*, "Booster Synchrotron," Fermilab-TM-405, 1973.

[2] W. Pellico *et al.*, "FNAL - the Proton Improvement Plan (PIP)," in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, p. 3409.

[3] K. Seiya *et al.*, "Beam Studies for the Proton Improvement Plan (PIP) - Reducing Beam Loss at the Fermilab Booster," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, p. 4027.

[4] N.V. Mokhov *et al.*, "Fermilab Booster Collimation and Shielding," in *Proc. PAC'2003*, Portland, OR, USA, May 2013, p. 1503.

[5] A. Drozhdin *et al.*, "Commissioning of the Beam Collimation System at the Fermilab Booster," Beams-doc-1223, Fermilab, 2004.

[6] I.S. Baishev, A.I. Drozhdin, N.V. Mokhov, X. Yang, "STRUCT Program User's Reference Manual," SSCL–MAN–0034, 1994.

[7] N.V. Mokhov, "The Mars Code System User's Guide," Fermilab-FN-628 (1995); MARS website: `http://mars.fnal.gov`

[8] MADX website: `http://mad.home.cern.ch/mad/`

[9] M. Seidel, "The proton Collimation System of HERA," report DESY 94-103, DESY, 1994.

[10] I. Strašík, I. Prokhorov and O. Boine-Frankenheim, *Phys. Rev. ST Accel. Beams*, vol. 18, p. 081001, 2015.

[11] L. Burnod, J.P. Jeanneret, "Beam losses and collimation in the LHC: A quantitative approach," report CERN SL/91-39, p.20, CERN, 1991.

[12] S. Cousineau, D. Davino, N. Catalan-Lasheras, J. Holmes, "SNS Beam-in-Gap Cleaning and Collimation," in *Proc. EPAC'2002*, Paris, France, Jun. 2002, p. 1019.

[13] R.J. Tesarek, B. Hartsell, V. Kapin, N.V. Mokhov, "Calculations of Power Deposited in the Booster Primary Collimators," Beams-doc-4998, Fermilab, 2015.