A NOVEL TWO STAGE COLLIMATION UNIT FOR FERMILAB BOOSTER*

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Abstract

A new two-stage collimation unit (2SC) for Fermilab Booster will be installed during 2024 summer shutdown. It is a supplementary collimator for existing single stage Booster collimators. Design details of this 2SC adapted to Booster conditions are described. Results of beam dynamics simulations on collimation efficiency and evaluation of collimator shielding with MARS code on this new system are presented. The analysis on beam dynamics shows that the system will help to collimate up to about 1% of the beam in a confined way and, prompt and residual activation meet Fermilab Radiological Control limits in current as well as during PIP-II era high intensity operation of the Booster.

INTRODUCTION

Fermilab Booster is an 8 GeV RCS accelerator. Presently, the Booster accelerates proton beam from 400 MeV to 8 GeV with about $2.45 \cdot 10^{17}$ protons per hour (pph), at $4.54 \cdot 10^{12}$ protons per Booster cycle (ppBc). During PIP-II era the beam injection energy will be increased to 800 MeV and a maximum of $4.8 \cdot 10^{17}$ pph at $6.7 \cdot 10^{12}$ ppBc is planned. It has been estimated that > 65% of the allowed ring wide beam loss of 475 Watt will occur below 2 GeV both in current operation as well as in future. During PIP-II era a significant part of this loss is expected to be at injection energy. Therefore, it is extremely important to collimate the beam and confine the particle losses at lowest possible energy *i.e.,* injection energy.

The purpose of a collimation system is to redistribute unavoidable beam losses in a controllable manner within the accelerator by concentrating beam losses in a dedicated well-shielded region and at the same time reduce beam losses on the remaining parts of the accelerator. The collimation system interacts and removes large amplitude beam particles which otherwise would be lost elsewhere on potentially sensitive equipment.

Currently we have a collimator system in Booster [1] with a low collimation efficiency which helps to collimate about 0.5% of the total particle losses at injection. So, a new 2-stage collimator (2SC) which comprises of both primary and secondary collimators in one unit is designed. This system along with the existing collimator is expected to improve the overall collimation efficiency in current and future operation of the Booster.

The new 2SC unit presented here is first of its kind in the Fermilab complex and is scheduled to be installed in the one of the 24 long straights section, Long 8 (L08), of the Booster during the 2024 summer shutdown. It will be tested and used during current operation and beyond. In this paper we describe the design details of the 2SC system and will show that the proposed shielding configuration and parameters guarantee the prompt dose levels on the berm, residual dose levels in the tunnel will be below the Fermilab/DOE administrative limits.

2SC UNIT AT BOOSTER LONG 8

Collimation Efficiency

Collimation efficiency ε of a single collimator is evaluated as a ratio of protons absorbed inside of collimators to a total number of primary beam protons hitting the primary jaws of the collimator. Figure 1 shows dependence of the collimation efficiency ε on the thickness of the copper primary collimator jaw t_{CU}. Initial evaluations at beam energy of 400 MeV [2,3] with simulation approach [4] using MADX code [5] for tracking in vacuum and MARS15 code [6] for tracking in collimator are shown with green curve. A comprehensive MARS simulations with MADX PTC tracker embedded inside MARS code using a detailed CAD geometry of the 2SC at 400 MeV [7] and 800MeV [8] are presented by red curve and by two blue boxed crosses, respectively. We will use this as a figure of merit for design of a new 2SC for future operation of the Booster.

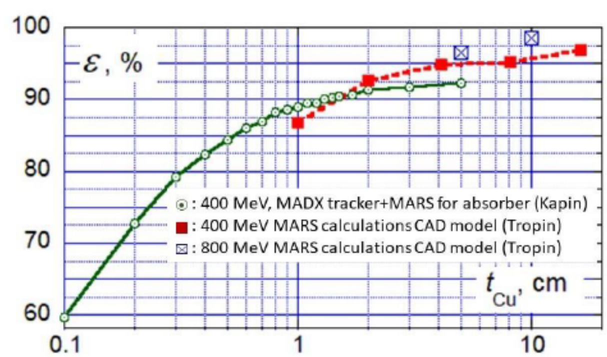

Figure 1: Collimation efficiency ε vs the primary copper jaw thickness t_{CU}.

In 2004, a collimator system that had a design, based on a classical 2SC scheme i.e., a thin primary and a thick secondary absorber located at a prescribed phase advance was installed in Booster periods 5-7. This collimator system never worked as planned in a 2SC scheme, due to some fundamental problems identified later in 2016 [4] and the collimation efficiency was <60%. Currently, they are operated as single stage collimators.

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Collimator Design

The new 2SC has a structure with a common "monolithic" shield embracing all primary and secondary collimation jaw in one unit [2, 3, 9] and it is about 4 m long. The collimation efficiency of such a 2SC unit has been evaluated to be >95% both at 400 MeV [2, 3, 7] and at energy of 800 MeV [8].

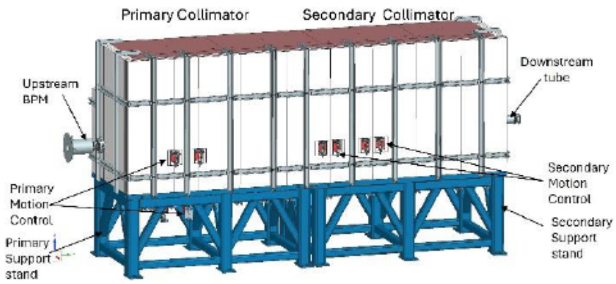

Figure 2: CAD drawing of the 2SC to be installed in the Booster tunnel.

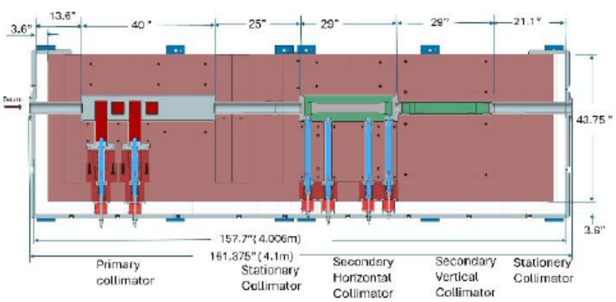

Figure 3: Plan view cross section of the 2SC unit showing the horizontal primary and secondary jaws.

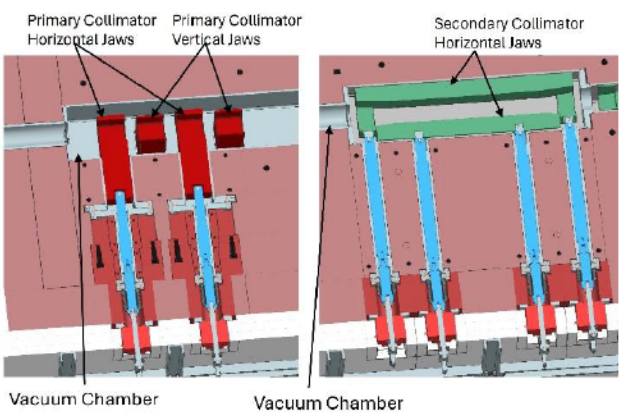

Figure 4: Horizontal sectional view of primary and secondary collimator jaws bisected in beam plane.

Figure 2 shows 3D CAD picture of 2SC unit to be assembled in the Booster tunnel along with outer steel and marble shielding. The beam comes from left to right. The primary and secondary collimator motion controls are placed aisle side and underneath. The plan view of the horizontal cross section is shown in Fig. 3 along with various dimensions. The body length of the unit is ~4 m. At the time of assembly, the entire inner unit can be assembled in two separate units *viz,* primary collimator region and secondary collimator region. The upstream horizontal and vertical primary collimators are chosen to be 10 cm thick solid copper. Four primary jaws shown in Figure 4, two horizontal and two vertical, can be moved inside the vacuum chamber toward the center of the beam line by ±1.5". The secondary jaws are made from stainless steel and are connected to plungers. These four jaws can be moved independently back and forth for horizontal collimators and up and down for vertical collimators by 1.5". Since air cooling is sufficient [10] no additional cooling is needed. Figures 5 and 6 show 3D view of horizontal primary collimator and vacuum chamber layout for primary and secondary collimators, respectively. The geometry of the vertical collimator is similar to that for the horizontal one. Since there are two sets of primary collimators of one type, they can be used to collimate beam from either side.

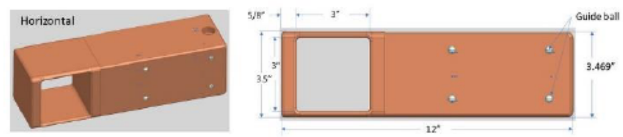

Figure 5: 3D and plan view of the primary horizontal copper collimator. The vertical primary has the same design features. .

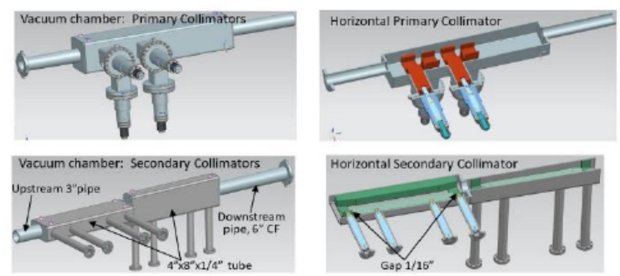

Figure 6: Primary and secondary collimator vacuum chambers with collimator jaws.

MARS SIMULATIONS

Before the installation of the 2SC in the Booster it is essential to examine radiological impact of this system during current and PIP-II era operation. In that regard, we have carried out extensive MARS simulations [7, 8, 11] with detailed geometry of the 2SC in the Booster ring. In this section, we first present our operational experience with the current collimator system and use findings along with the simulation results to extrapolate to PIP-II era scenarios.

Observed Beam Losses in Current Operation

Table 1 shows measured residual activation levels at 1 foot from a routing radiation survey prior to tunnel access. The data displayed is from an operating throughput condition of $2.45 \cdot 10^{17}$ protons/hr. The data clearly shows there is high concentration of beam losses at injection, collimation, extraction regions, significantly higher near collimation region. If the losses at extraction are not counted, then the activation distribution number in parenthesis represents the relative distribution of loss at the lowest energy of the cycle. This demonstrates that the collimation region currently is responsible for about half of the activation around the ring.

Table 1: Residual Activation in Booster Tunnel at 1 ft.

Loss Location	Loss level *mrem/hr*	Activation Distribution
Injection Area	300-400	14% (23%)
Collimation Area	300-700	48% (55%)
Extraction Area	500	20% (0%)
Rest of ring	< 50	18% (21%)

Table 2 lists the injected beam parameters, operational assumptions, anticipated power deposited on collimators for current and PIP-II era operation.

For this assessment we will assume that the beam loss is divided equally among collimators.

Table 2: Beam Power per Collimator

Parameter	Current	PIP-II	Units
Beam energy	400	800	MeV
Protons per hour	$2.45 \cdot 10^{17}$	$4.80 \cdot 10^{17}$	pph
Protons per sec	$6.81 \cdot 10^{13}$	$1.33 \cdot 10^{14}$	pps
Protons per cycle	$4.54 \cdot 10^{12}$	$6.67 \cdot 10^{12}$	ppBc
Repetition rate	15	20	Hz
Beam power	4.4	17.1	kW
Assumed Efficiency	94	98	%
Power lost	261.3	341.3	W
Fraction on collimators	0.5(of 6%)	0.5(of 2%)	-
Power on all collimators	130.7	170.7	W
Number of collimators	3	4	-
Power per collimator	43.6	42.7	W
Scraping rate for MARS	$8.8 \cdot 10^{11}$	$3.3 \cdot 10^{11}$	pLps

Results from MARS Simulations

Figure 7 shows the modelled 2SC system in MARS simulations which is based on the installation assembly drawings. The model does not include any Booster surrounding magnets or equipment. However, the tunnel walls and berm around the tunnel are considered.

Figure 8 shows the predicted prompt longitudinal and transverse (at its maximum of proton shower) distribution dose rate (DR) for beam particle losses shown in Table 1. The ground surface is shown by black solid line at $x \approx 5.33$ m. The simulations show the maximum DR at the surface is around $3 \cdot 10^{-2}$ mrem/h, which satisfies the radiological limit for "No precautions needed".

Residual DR on contact have been evaluated [7, 8, 11], assuming 100 days of continuous irradiation followed by 4 hours without beam. The maximum residual DR found to be well below 20 mrem/hr [7, 8] in the region where accelerator personal normally access. Figure 9 shows the estimated residual DR distribution in the Booster tunnel for proposed location for 2SC [11]. Residual DR on aisle side surfaces of collimator marble shields are <2 mrem/hr and on the aisle side of concrete walls are less than 33 mrem/hr and, on other regions of interest are marked on the figure.

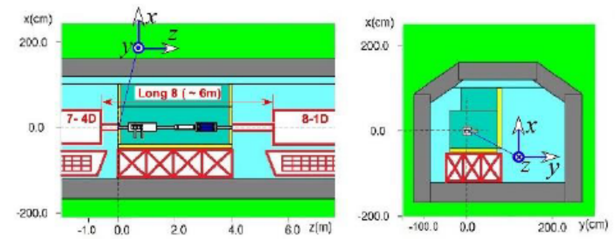

Figure 7: Side and front view of the 2SC MARS model.

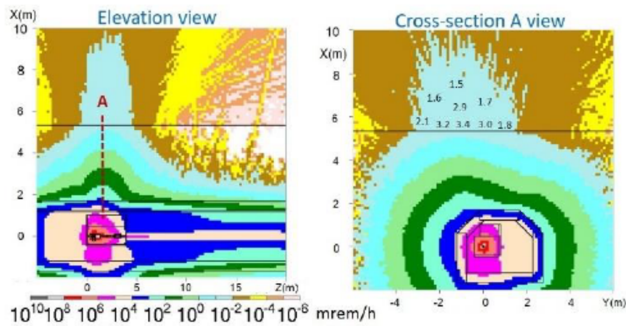

Figure 8: The prompt dose distribution around of 2SC.

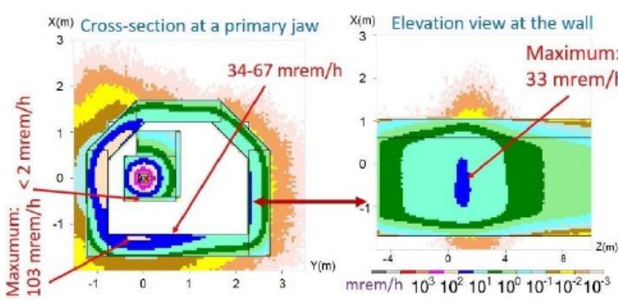

Figure 9: Residual dose distribution around of 2SC. The shown are transverse cross-section at a primary jaw (left panel) near $z \approx 0.5$ m and the elevation view at the wall in front of a primary jaw (right panel) at $y \approx 2$ m.

In summary, a new 2SC for Fermilab Booster has been designed. The salient feature of the collimator system is described. We also present results of MARS simulations for prompt and residual dose rate and have shown that the 2SC unit will satisfy needed radiological requirements.

ACKNOWLEDGEMENTS

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