LAYOUT OF PROJECT-X FACILITY: A REFERENCE DESIGN*

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Abstract

Project-X is a proposed high intensity proton facility to be built at Fermilab. It will be a multi-user facility which can support several experiments simultaneously. In the current scenario, the facility would be built in three stages. Each stage is associated with compelling scientific programs and is in synergy with existing Fermilab infrastructure. This paper presents the current reference design and discusses the main motivations and requirements driving the optics and physical layout.

INTRODUCTION

Project-X is a proposed high intensity proton facility to be built at Fermilab. Given the present economic environment, a staging strategy has been developed. The facility would be built in three stages. Each stage is associated with compelling scientific research programs and planned so that construction of each new stage has minimal influence on the operation of preceding ones. This approach has the benefit of limiting downtime during construction. A schematic of the Project-X facility is shown in Fig 1. A detailed description of the staging approach is presented elsewhere [1].

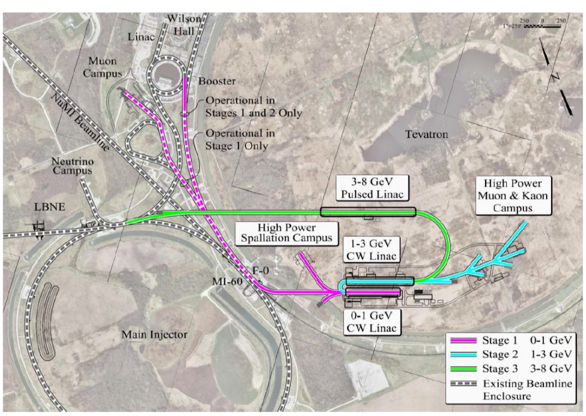

Figure 1: Layout of Project-X facility.

Success of the Project-X facility is critically dependent on the robustness of the superconducting (SC) continuous wave (CW) linear accelerator (Linac) design. While the reference design parameters [1] have been established, the optics is still evolving to incorporate technical constraints and to address issues that may potentially cause degradation of beam quality and particle losses. In this paper we describe recent changes in the beam optics.

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STAGE -I

The most challenging issues associated with Project-X facility would be addressed at Stage-1 which comprises a room temperature front-end followed by a 1 GeV SC CW linac delivering a 1 MW of beam power.

Ion Source, LEBT & RFQ

The front-end of Project-X consists of an ion source, a low energy beam transport (LEBT) section, an RFQ and a medium energy beam transport (MEBT) section. The ion source [2] operating in dc mode is capable of delivering a beam of H^- ion at 30 keV at maximum current of 10 mA. It is followed by the LEBT which includes three solenoids, a slow switching dipole magnet, a chopper assembly and diagnostic devices to characterize the beam. The chopper consists of a kicker and a beam absorber. It will primarily be used to produce variable low duty pulses during commissioning; it can also serve as pre-chopper to assist the MEBT high bandwidth chopping system. A detailed description of the LEBT layout and its component was presented elsewhere [1].

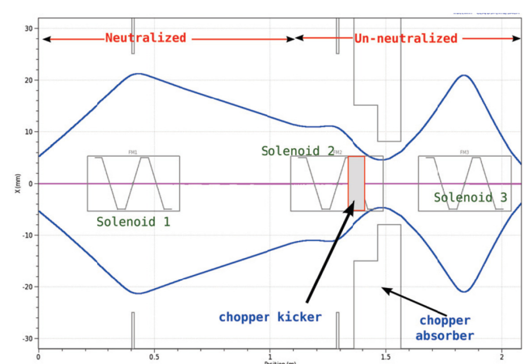

Figure 2: $3\sigma_{RMS}$ transverse beam envelope along LEBT (shown for fully neutralized operation).

A LEBT with solenoidal focusing usually requires neutralization to mitigate strong space charge defocusing. However, chopping of a neutralized beam can be problematic because the typical neutralization time is a few tens of micro-seconds, resulting in a time dependent optical perturbation. The Project-X LEBT design attempts to address this issue by incorporating two regions: (i) a fully neutralized region which extends from exit of the ion source to upstream edge of the second solenoid and (ii) an un-neutralized region from that point to the RFQ entrance port. Alternatively, the LEBT can also be operated in fully neutralized regime. Figure 2 shows a $3\sigma_{RMS}$ transverse beam envelope for fully neutralized operation. To

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minimize spherical aberrations through the solenoids, the beam transverse size is kept below half of the solenoids radial aperture [3]. Emittance growth in the LEBT occurs in the un-neutralized region and is driven by space charge. The LEBT is followed by an RFQ operating in CW mode at a resonant frequency of 162.5 MHz. It accelerates the beam to 2.1 MeV and provides longitudinal beam structure. Numerical simulations predict 99.8% beam transmission for nominal operation at 5 mA beam current. However, both transmission and output emittances strongly depend on beam matching at entrance of the RFQ. Figure 3 shows the evolution of the normalized RMS beam emittances through the LEBT and the RFQ for two modes of operation of the LEBT: (i) a partially neutralized LEBT (un-neutralized region after second solenoid) and (ii) a fully neutralized LEBT. It can be observed that beam emittances through the RFQ are significantly larger for partially neutralized LEBT operation. This is a consequence of non-linear space charge effects. Beam transmission through the RFQ is also reduced to 98.4 %.

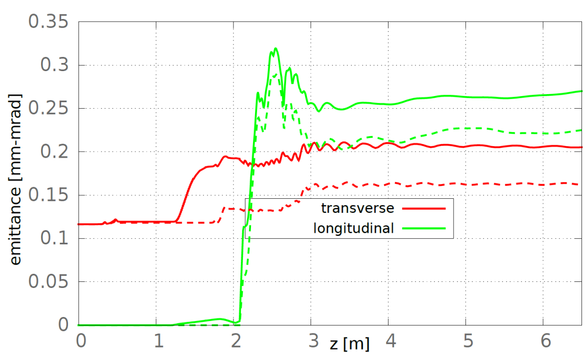

Figure 3: Normalized RMS beam emittances through LEBT and RFQ. Solid: LEBT with un-neutralized section. Dashed: fully neutralized LEBT.

MEBT & 1GeV SC CW Linac

The RFQ is followed by the MEBT and a 1 GeV SC CW linac. In order to improve the robustness of the design, the beam optics has been optimized. It can now accommodate, at the MEBT entrance, a longitudinal emittance larger than the reference design value [1]. The layout and beam optics are discussed elsewhere [4]. Changes in beamline elements are presented in [5]. A significant change is the introduction of a new β_G =0.92 cavity in the high energy 650 MHz section. This cavity has larger aperture (118 mm) which is beneficial in terms transverse acceptance in this section and avoids potential trapping of higher order modes. This cavity is therefor well suited to a future upgrade for higher current operation. The optics described in the reference design report was based on 5-cell, β_G =0.90, 650 MHz cavity (designed with aperture of 100 mm) in high energy section; the new cavity provides similar RF performance with minimal influence on beam optics.

1 GEV EXTRACTION LINE

Stage 1 of Project-X will provide 1 MW of beam power. This power will be distributed between a 1 GeV experimental area and the Booster/Muon campus using a special extraction scheme designed to allow both experimental facilities simultaneously. This is achieved by multiplexing the beam time structure. For stage 2, an additional MW of beam power will be delivered to the 1-3 GeV CW linac using the same extraction line. Figure 4 shows a conceptual layout of the extraction line which includes a vertical deflection unit (VDU) and a horizontally bending Lambertson magnet. The vertical deflection unit is composed of an RF deflecting cavity with trim dipoles positioned at the upstream and downstream ends.

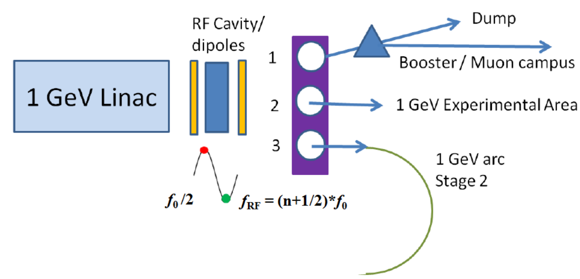

Figure 4: Conceptual design of 1 GeV extraction line.

RF Deflecting Cavity and Trim Dipole Magnets

The RF deflecting cavity at the end of 1 GeV linac splits the beam into two equal parts by imparting equal and opposite vertical kicks to successive bunches. The kick direction depends on the relation between the beam phase and the rf phase. Consequently, with f_0 representing the bunch frequency, the required rf frequency is

$$f_{RF} = (n + 1/2)f_0 \tag{1}$$

where n is an integer. The deflecting cavity at 1 GeV is designed to operate at 406.25 MHz (n and f_0 are equal to 2 and 162.5 MHz respectively). It is capable of providing maximum transverse voltage ($\Delta pc/e$) of 7 MV which corresponds to a deflecting angle θ of 4 mrad at 1 GeV. The trim dipoles on both sides of the cavity are identical and steer the beam in the vertical plane. Table 1 presents a summary of the cavity and dipole setting required to direct the beam to the different experimental facilities at stage I and stage II.

Lambertson Magnet

The VDU is followed by a 3-way Lambertson magnet. If there is no net deflection from the VDU, the beam goes through the field free region along the axis of Lambertson magnet and is delivered to the 1 GeV experimental area. However, when the beam experiences a net deflection from the VDU, it passes either through the upper or lower field region of the Lambertson and is steered horizontally. The direction of the horizontal steering is determined by the

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Table: 1 Operational scenarios for the VDU. 4th column (Dipole) is the total deflection from both dipoles.

Stage	Destination	deflecting cavity	Dipole	DSW
1	Muon Campus	+θ	+θ	
	1 GeV EA	-θ	+θ	
	Booster	off	+2θ	
	Dump	off	+2θ	on
2	1 GeV EA	+θ	-θ	
	Booster	off	+2θ	
	Dump	off	+2θ	on
	1 GeV arc	-θ	-θ	

sign of the net vertical deflection (+/-θ) from the VDU. Figure 5 shows beam separation scheme through Lambertson magnet.

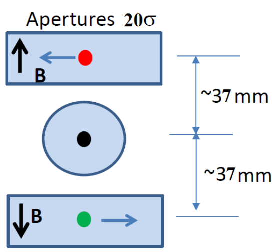

Figure 5: Schematic of 3-way Lambertson magnet. The beam is steered toward the left or the right depending on the sign of the vertical deflection imparted by the VDU.

Beam Optics through 1GeV Extraction Line

Figure 6 shows $1\sigma_{RMS}$ beam envelope through the 1 GeV extraction line. The RF deflecting cavity is set to provide a vertical deflection angle of 3 mrad while each dipole provides a 1.5 mrad vertical steering. A special quadrupole doublet with large aperture of 120 mm is placed just before the Lambertson magnet to cancel the vertical slope of the beam centroid so that it can enter the Lambertson magnet field region in the horizontal plane. The VDU to Lambertson distance is chosen to provide enough beam separation (15 - 20 σ_{RMS}) between deflected and undeflected beam. With the present settings, this separation is 20 σ_{RMS} (37 mm) (as mentioned in Fig 5). The Lambertson magnet is 1 m long; it provides an integral magnetic field of 0.2 T-m, corresponding to a $\sim$35 mrad deflection in the horizontal plane. The distance from the Lambertson to the first element of each beamline is optimized to provide enough horizontal separation. It can be observed from Fig 7 that introduction of the the extraction line does not contribute to emittance growth. The impact on the downstream optics is expected to be minimal. Minor retuning of the first section of the subsequent stage may be required to match the beam parameters at the entrance.

STAGE -II & STAGE -III

At stage II, 1 MW of beam power will be delivered to the 1-3 GeV SC CW linac through a 180^0 arc for further acceleration. Extraction line at the end of this stage will distribute 3 MW of beam power to different experimental facilities using a concept similar to the one discussed for

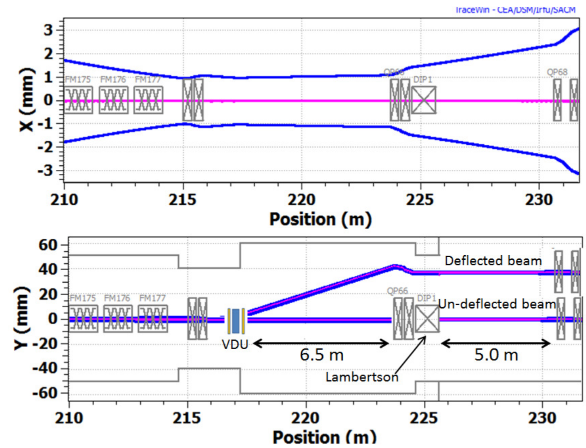

Figure 6: Beam RMS envelope in transverse plane through 1 GeV extraction line.

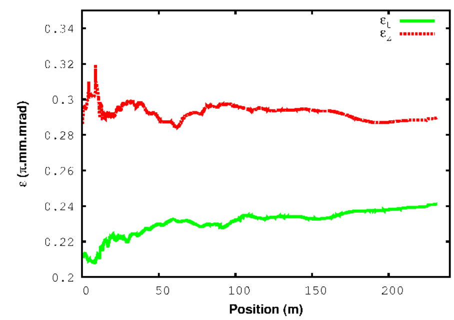

Figure 7: Longitudinal (green) and transverse (purple) beam emittance through stage 1.

the 1 GeV extraction line. In the final stage, 350 kW of beam power will be transported to a 3-8 GeV pulsed linac through another 180^0 arc. Details of the beam optics for the 1-3 GeV CW linac and the pulsed linac are discussed elsewhere [4].

SUMMARY

The beam optics is compatible with the Project-X staging strategy. Furthermore, it provides sufficient acceptance to accommodate, if necessary, larger emittances coming out of the RFQ.

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