THE PROJECT-X 3 GEV BEAM DISTRIBUTION SYSTEM*

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Abstract

In the Project X facility, a 3 GeV H^- CW beam is delivered to three users, simultaneously. This will be accomplished by selectively filling appropriate RF buckets at the front end of the linac then utilizing a RF splitter to transversely separate the bunches vertically to three different target halls. A compact TE_{113} squashed-wall superconducting RF cavity has been proposed to produce the initial vertical deflection. The transport line optics, cavity design parameters, and cryogenic system requirements will be presented.

INTRODUCTION

The proposed Project-X facility is a multi-MW proton source under development at Fermilab [1]. The goal of this facility is to enable a world class experimental program in Kaon, Muon, and Nuclear Physics as well as provide increased beam power enabling the next generation of a Long Baseline Neutrino Experiment. The facility is based on a 3 GeV CW linac accelerating H^- ions. Approximately 90 to 95% of the ions will be directed toward the 3 GeV experimental area which will be housed in up to three target halls.

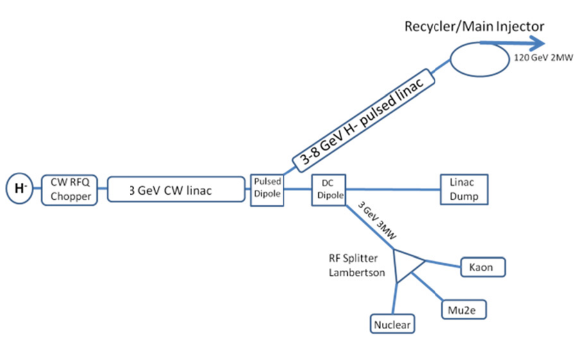

Figure 1: Schematic layout of Project-X.

The remainder of the ions will be directed toward a 3 to 8 GeV pulsed linac. The 8 GeV H^- ions will be transported to the Recycler/Main Injector complex for acceleration to 120 GeV providing in excess of 2 MW of beam power to a neutrino production target. A schematic of the facility and 3GeV switchyard are shown in Figure 1. With the desire to split the H^- beam three ways, a RF separator is utilized to direct two quarters of the beam to one user (Mu2e), one quarter to another user (Kaon), and one quarter to the third (Nuclear) user as shown in Figure 2. The beam structure is shown in Figure 3. The bunch frequency is 162.5 MHz. The bunch train width for the Mu2e experiment is 100ns with a repetition frequency of 1 MHz. The bunch sequence for Kaon and Nuclear experiments is 27 MHz. The RF deflection is provided with a set of RF cavities with the TE_{113} deflecting mode operating at the frequency $f_0(m \pm 1/4)$, where f_0 is the bunch frequency. The operating frequency of the deflecting RF structure is limited (i) by the beam longitudinal size – at high frequency and (ii) by the cavity transverse size – at low frequency. The cavity should have a reasonable aperture (a compromise between the deflecting properties and possible beam loss heating the cavity). Operating the structure in the CW regime at 446.875 MHz ($m=3$) with a deflection angle of $\Delta pc/e \sim$ 10 MeV it is possible to achieve a total deflection angle of approximately ± 2.6 mr.

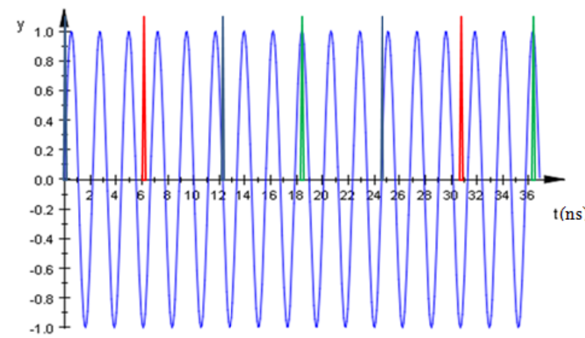

Figure 2: Transverse kick from the 446.875 MHz RF (purple curve) to 162.5 MHz bunches to Mu2e (blue), Kaon (red), and Nuclear (green).

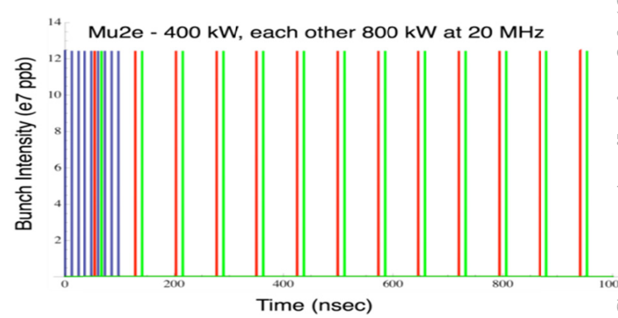

Figure 3: Time structure of the bunches for three experiments are shown for Mu2e (blue), kaon (red), and Nuclear (green).

OPTICS

To minimize the required deflection angle and hence power requirements of the deflection cavity, the separation scheme will utilize this cavity to select the aperture of a downstream 3-way horizontal bending Lambertson. The RF separator will impart a small vertical angle based upon the phase of the beam wrt the RF

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separator phase. The total vertical deflection angle required is dependent on the beam size at the Lambertson and the vertical apertures of the two field regions and field free region. As this Lambertson is expected to distribute up to 3 MW beam power to the experimental facility, the Lambertson apertures should not be the limiting aperture. A conservative estimate of the required aperture would dictate an aperture that is at least a factor of two to three greater than the 99% beam envelope. This gives rise to a separation of 12σ τo 18σ + Δs, the septum thickness of the Lambertson at the horizontal position of the un-deflected beam. The septum thickness at the position of the un-deflected beam must not saturate at the expected dipole field of 0.64T. This leads to an estimated septum thickness of approximately 5 mm.

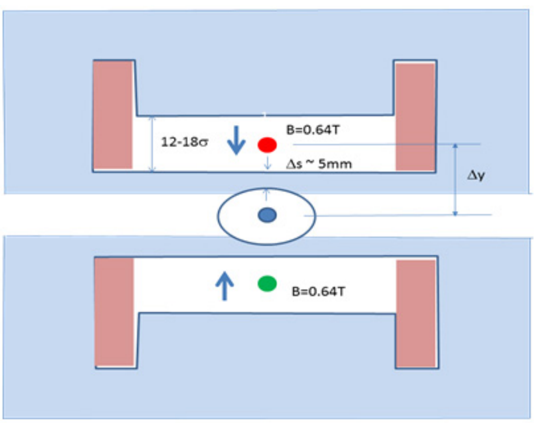


Figure 4: Beam positions at the entrance of the 3 way horizontal Lambertson for Mu2e (blue), Kaon (red), and the other experiment (green). Arrows indicate field direction.

For a normalized rms transverse emittance of 0.37 mm-mr at the entrance to the Lambertson, the rms vertical distribution varies from 1.25 mm, at the entrance, to 1.02 mm at the exit of the 2m Lambertson. Using the 18σ figure the separation at the entrance to the Lambertson should be ±27.5 mm. The required deflection angle, Δθ, given by $\Delta y/(\beta_c\beta_L)\sin\varphi$, where βc and β_L are the beta functions at the cavity and Lambertson, respectively, and φ is the vertical phase advance between the two locations, is ±1.3 mr. This is nearly a factor of two less than the maximum available in a 3-cell cavity such that cavity can run at a lower excitation or optionally a 2 cell cavity could be utilized instead. Figure 5a-b shows a) the layout of the cavity and Lambertson and b) the beam σ through the cavity and Lambertson. Note that the vertical size of the beam at the cavity is larger than at the Lambertson to minimize the beam size at the Lambertson while increasing the product $\beta_c\beta_L$, thus reducing the required angle. Preliminary estimates of longitudinal emittance growth on the un-deflected beam and transverse emittance growth of the deflected beam indicate this is not an issue for beam transported to a fixed target.

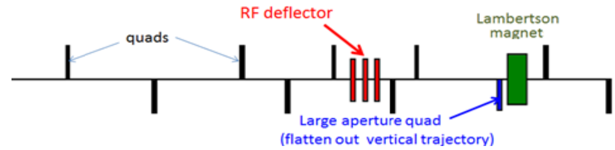


Figure 5a: The bunches are separated in vertical direction by RF cavity by ±27 mm and then deflected in horizontal direction by 3-way Lambertson magnet.

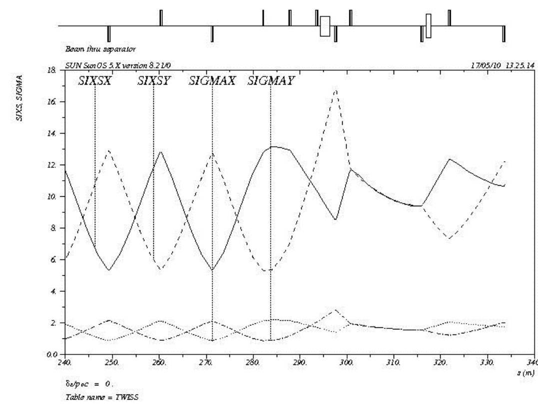


Figure 5b: Beam size at the RF separator and 3-way Lambertson.

RF CAVITY DESIGN

In [2] we presented the design of deflecting RF structure with the TM_{110} operating mode based upon the KEKB crab cavity which satisfied the requirements for RF separation. An alternative superconducting deflecting cavity – parallel-bar cavity (PBC) both rectangular and ellipsoidal was proposed by J. Delayen in [3].

Because of TE type of operating mode, the region between the parallel bars and the outer walls can be removed. Figure 6 shows the electric (left image) and magnetic (right image) field distribution in PBC (top image) and modified “squashed wall” cavities (lower image).

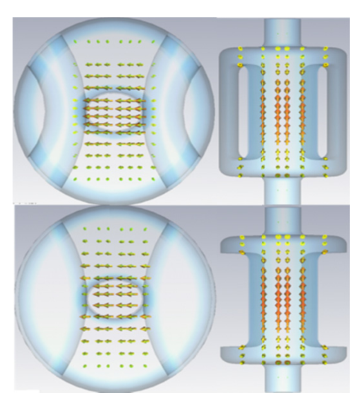
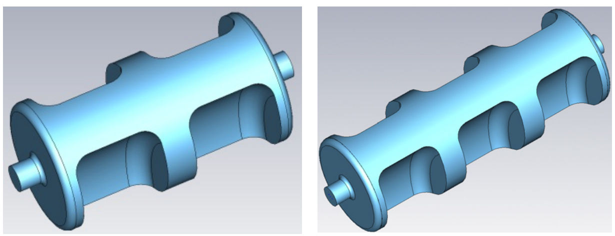


Figure 6: EM field distribution of the TE_{111}-like modes in PBC (upper) and “squashed walls” cavity [3] (below).

A PBC modification, “squashed walls” cavity [3] has about the same parameters as the parallel bar cavity, but is much simpler for manufacturing and doesn’t have regions (between bars and the outer walls) were multipactoring may develop.

The surface magnetic field is one of the major limitations during the cavity RF design. If the surface magnetic field is limited to ~70mT the kick is about 3.3 MeV per single cavity. To achieve the required total kick of 1.3 mr (~5MeV) we propose to use a single multi-gap cavity shown on the left in Figure 7. If deflection requirements are increased, the number of cells could be increased to three (as shown on the RHS of figure 7). The main RF parameters of these cavities are shown in Table 1.



Figures 7: FNAL proposed "squashed" TE_{112} and TE_{113} deflecting cavities.

A "squashed walls" TE_{112} and TE_{113} cavities are simple and compact. The 3 cell cavity has the length of 1 m and diameter of 0.37 m instead of 4.5 meter-long, 1 m in transverse size 3-cavity KEK-type RF system[2]. The new cavity sizes are close to FNAL 650 MHz cavity. Thus, all the same surface processing and test facilities may be used.

Table 1: Parameters for 2 and 3 cell "squashed wall" cavities.

Parameter	**2 cell cavity**	**3 cell cavity**
Frequency	446.875 MHz	
Mode	TE_{112}	TE_{113}
R/Q*	440 Ω	503 Ω
G	109 Ω	117 Ω
V_{kick}	6.6 MeV	10 MeV
E_{peak}	33.7 MeV/m	34 MeV/m
B_{peak}	74.4 mT	74 mT
Cavity Diameter	327 mm	366 mm
Aperture	75 mm	75 mm
Cavity length	810 mm	1005 mm

*$R/Q=V_{kick}^2/2\omega W$, where W is the stored energy

Input power requirements are determine mainly by amplitude of microphonics δf [2]. $P_{inp} \sim V_{kick}^2/[(R/Q)\cdot f/\delta f]$. For a 3-cell "squashed walls" cavity running at 5 MeVand for δf=15 Hz, P_{inp}~1.9 kW.

CRYOGENIC REQUIREMENTS

The microphonics amplitude is determined by expected He pressure variations and df/dp value. Minimization of *df/dp* is one of the major goals during the cavity mechanical design. The helium pressure fluctuation budget is limited to 0.2 mbar rms. The splitting cavity is located an approximately 300 m downstream from the CW linac cryogenic plant. Cost benefit analysis of using a transfer line from the CW linac main cryogenic plant versus a dedicated cooling system was conducted. As a result, reuse of a Tevatron satellite refrigerator with a single stage Tevatron cold compressor is envisioned. Such cryogenic system will enable to operate the cavity at ~3.8K within required pressure fluctuation budget. The cryogenic losses from RF power heating are given by $V_{kick}^2/\{2(R/Q)Q_0\}$, with Q_0=1E-9 given by G/R_s, G is the geometrical factor and R_s is the shunt impedance (~100nΩ at 3.8 K). For the assumed RF power level of 5 MeV, the cryogenic losses are approximately 28 W for the 2-cell cavity and 25 W for the 3-cell cavity. Powering these cavities at their peak voltages (listed in Table 1) leads to cryogenic losses of approximately 50 W and 100 W for the 2- and 3-cell cavities, respectively. These losses are still within the capabilities of the proposed cryogenic solution.

CONCLUSION

We have proposed a beam line optical solution for a two step 3-way splitting station based upon a vertical RF splitting cavity and horizontal 3 way Lambertson. A new compact "squashed wall" multi-cell RF cavity is proposed which is easy to manufacture. The RF power requirements have been determined and are quite reasonable. Cryogenic losses and requirements have been determined and a stand-alone reused cryo plant is proposed.

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[1] Project X Initial Configuration Document-2, Edited by P. Derwent, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=230
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