THE BEAM SPLITTER FOR THE PROJECT X*

N. Solyak#, I. Gonin, S. Nagaitsev, D. Johnson, and V. Yakovlev, Fermilab, Batavia, IL 60510, U.S.A.

Abstract

In the Project X facility, a 3 GeV, H^- CW beam is delivered to three users simultaneously by way of selectively filling appropriate RF buckets at the front end of the linac and then RF splitting them to three different target halls. With the desire to split the H^- beam three ways, an RF separator directs two quarters of the beam to one user (Mu2e), one quarter to another user (Kaon), and one quarter to the third (unidentified) user. The natural way is to use a SC structure with the deflecting TM110 mode. Basic requirements to the deflecting RF structure are formulated and design of the deflecting SC cavities is presented.

INTRODUCTION

Project-X is a multi-MW proton source is under development at Fermilab [1]. It will enable a world-class Long Baseline Neutrino Experiment (LBNE) via a new beam line pointed to DUSEL in Lead, South Dakota, and support a broad suite of rare decay experiments. The facility is based on 3-GeV CW linac. 5-9% of the H^- beam is accelerated in a SRF pulse linac or RCS for injection to Recycler/Main Injector. The main portion of H^- beam from the linac is directed to three different experiments as shown in Figure 1.

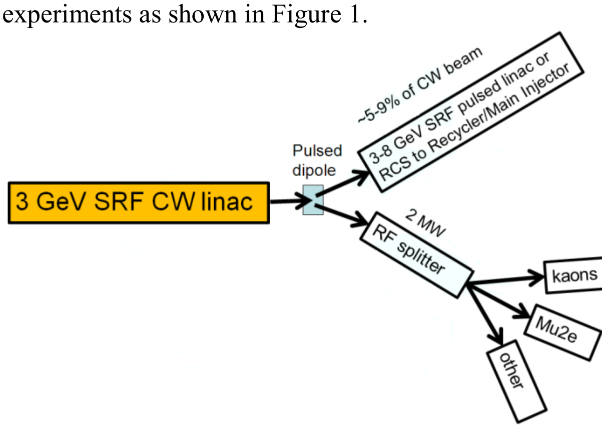

Figure 1: Concept of Project X proton source.

With the desire to split the H^- beam three ways, an 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 (unidentified) user (see Figure 2). The beam time structure is shown in Figure 3. Each bunch contains 9e7 of H^-. The bunch sequence frequency for the Mu2e is 162.5 MHz (for the RFQ frequency of 325 MHz) and the bunch train width is 100 nsec when the train repetition rate is 1 MHz. The average beam current is 1 mA. The bunch sequence for Kaons and other experiment is 27 MHz. The beam power for Mu2e is 400 kW, and 800 kW for each other experiment. This time structure is provided by bunch-by-bunch the chopper in the accelerator medium beam energy transport line [1]. The natural way to provide RF deflection is to use a set of RF cavities with the deflecting TM_{110} mode operating at the frequency $f_0(m\pm1/4)$, where f_0 is the bunch sequence frequency (f_0=325 MHz). 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 (compromise between deflecting properties on one hand, and possible current intercepting on the other hand). Operating the structure in CW regime at 406.25 MHz (m=1). with a deflection of $\Delta pc/e$ ~ 7.5 MeV, it is possible to achieve a total deflection angle of approximately ±2.5 mrad.

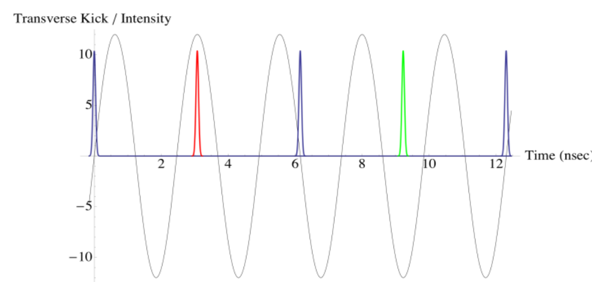

Figure 2: Transverse kick for the bunches directed to Mu2e (blue), Kaon (red) and other experiment (green).

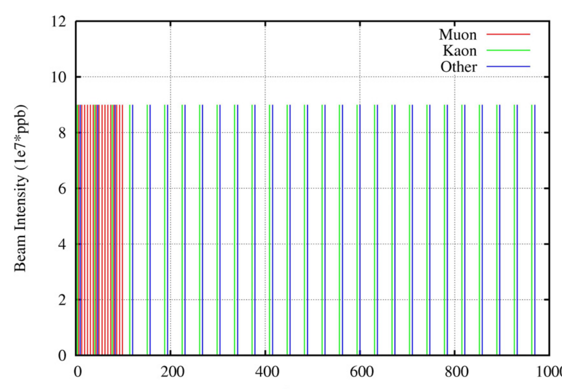

Figure 3: Time structure of the H^- beam. The bunches for Mu2e are shown in blue, the bunches for Kaon experiments are shown in red, and for other experiments in green.

OPTICS

To minimize the required deflection angle, the separation scheme will utilize the RF separator 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 separator phase

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#solyak@fnal.gov

(figure 2). The total deflection angle required is dependent on the required vertical separation and aperture of the Lambertson.

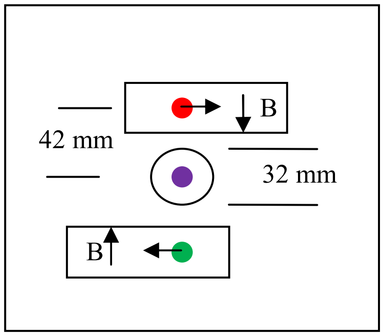

Figure 4: Beam positions at entrance of 3 way horizontal Lambertson for Mu2e (blue), Kaon (red) and other experiment (green).

An initial estimate for the required separation at the Lambertson is approximately 40 to 50 mm (see figure 4). To accomplish this, the Lambertson was placed approximately 20 meters downstream of the RF separator with a vertical deflection of 2.5 mrad. from the RF separator, or about 10 MeV of transverse kick. Figure 5 shows the expected beam size in the region of the RF separator and downstream Lambertson. A large aperture defocusing quad is used upstream of the Lambertson to compensate the vertical kick from the RF separator. All fields and gradients are consistent with minimum H- field stripping. The field in the Lambertson produces 100 mrad bend to allow sufficient separation for installation of the downstream quad in each line.

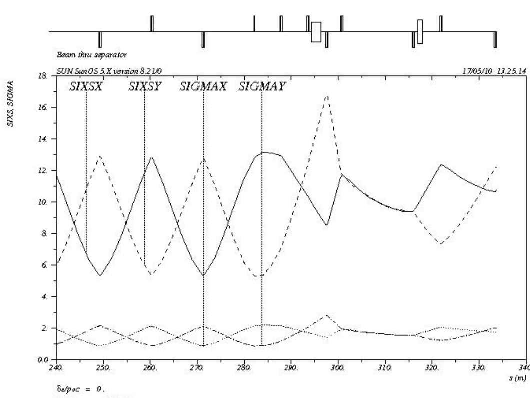

Figure 5: Beam size at RF separator and 3 way Lambertson.

GENERAL

The splitter for 325 MHz RFQ option should provide the following parameters:

- Operating frequency: 406.25 MHz;
- Transverse kick: ~10 MeV.

There is a deflecting cavity close to required parameters, it is a KEKB crab cavity [2]. The cavity operates at 509 MHz and provides a kick of 1.44 MeV. The cavity concept is shown in Figure 6. The cavity is not axially symmetric (so called squashed-cell shape cavity), which has the cross section of racetrack shape to push up the resonance frequency of unwanted degenerate TM_{110} mode to 700MHz. A coaxial coupler inserted into the cavity cell is used to extract the lowest 430MHz TM_{010} acceleration mode and the higher TE mode outside the cavity. KEKB crab cavity shape is optimized in order to accommodate the HOM absorbers necessary to suppress parasitic modes excited by ~2 A beam.

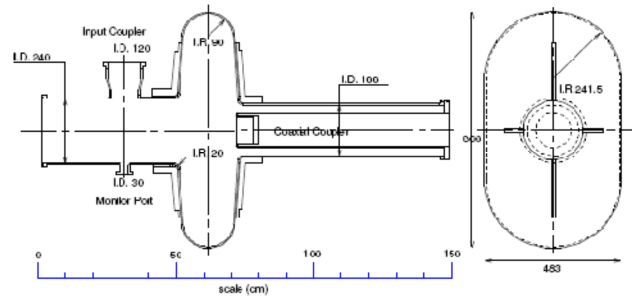

Figure 6: Conceptual design of the KEKB crab cavity.

Parameters of the cavity are shown in Table 1 including R/Q, G-factor and maximal surface magnetic field B_{sp} and maximal electric field E_{sp} over the kick voltage V_{kick}. The cavity R/Q is defined as $(V_{kick})^2/2\omega W$ (W is the energy stored in the cavity, ω is cyclic frequency).

Table 1: Parameters of KEKB crab cavity.

Parameters		**Units**
R/Q	23.4	Ohm
G-factor	220	Ohms
B_{sp}/V_{kick}	41.5	mT/MeV
E_{sp}/V_{kick}	14.4	MV/m/MeV

The cavity was tested at 4.2 K, and E_{sp} reached to 30MV/m (V_{kick}=2.1 MV and B_{sp} =87 mT) keeping Q_0 values higher than 1e9, see Figure 7. Operating value is E_{sp}=21MV/m, or V_{kick}=1.44 MV and B_{sp} =60 mT.

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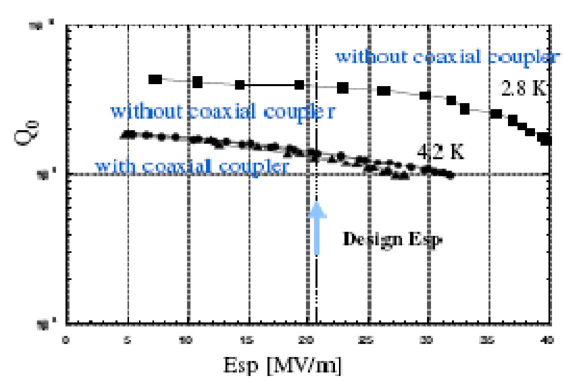

Figure 7: Q_0 value versus maximal surface field for KEKB crab cavity.

For Project X a cavity with similar design is suggested without the coaxial HOM damper which is not necessary for the beam current of 1 mA. The cavity layout and field distribution is shown in Figure 8. Parameters are shown in Table 2.

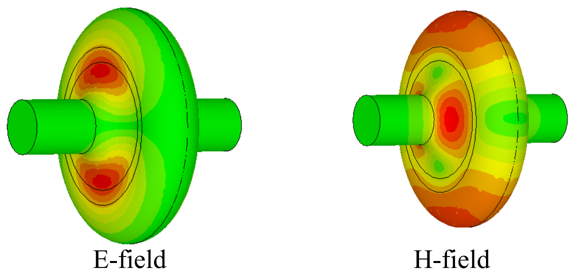

Figure 8. The Project X beam splitter cavity layout and field distribution over the surface.

Table 2: Parameters of the Project X splitter cavity.

Parameters		Units
R/Q	27	Ohm
B_{sp}/V_{kick}	19.2	mT/MeV
E_{sp}/V_{kick}	7.8	MV/m/MeV
Longitudinal size	440	mm
Vertical size	865	mm
Horizontal size	962	mm
Aperture	220	mm

The cavity spectrum is shown in the Table 3.

Table 3: Spectrum of the Project X splitter cavity.

Monopole		Dipole1		Dipole2	
F,MHz	R/Q,Ω	F,MHz	R/Q,Ω	F,MHz	R/Q,Ω
289.2	118	406.25	27.3	427.9	25.2
557.1	1.5	529.1	6.2	528.3	6.1
635.7	6	691.4	0.16	695.7	0.04
692.6	0.001	726.7	0.03	743.6	0.14
730.1	16	759.5	2.8	759.4	2.5
825.2	0.002	797.6	0.08	797.8	0.12

If the surface magnetic field is ~60-65 mT, the kick is 3.1-3.4 MeV per cavity. It means that three cavities are necessary in order to achieve the total kick of 10 MeV, each cavity provides the kick of 3.3 MeV.

RF power requirements are composed by

- power requirements necessary to maintain the RF field in the cavity (Q_0=1.e9),

$$P = \frac{(V_{kick})^2}{\left[2\left(\frac{R}{Q}\right)Q_0\right]} = 200\ \mathrm{W/cavity}$$

- Power necessary for compensation of the beam loading caused by misalignment ($\Delta x=\sigma_x$=0.5 mm; U_{ind}<0.01V_{kick}), $U_{ind}= I_0\ (R/Q)\ (k\ \Delta x)Q_{load} < 0.01V_{kick}$; Q_{load} < 3e8 and

$$P = \frac{(V_{kick})^2}{\left[2\left(\frac{R}{Q}\right)Q_{load}\right]} = 700\ \mathrm{W/cavity}$$

- Power necessary for microphonics compensation: Q_{load}~1.3e7 ($\Delta f \sim 6\sigma_f$=30 Hz for σ_f= 5 Hz) and

$$P = \frac{(V_{kick})^2}{\left[2\left(\frac{R}{Q}\right)Q_{load}\right]} = 16\ \mathrm{kW/cavity}$$

Thus, the total power does not exceed 60 kW. Note that power required for microponics may be significantly reduced by fast piezo-tuner. Total cryogenic losses are about ~0.6 kW at 4.2 K

Requirements for parasitic mode damping:

- Monopole modes (LOM):

  $P = 2I_0^2\frac{R}{Q}Q_{load} < 0.1P_{cryo} = 20W$

  Q_{load} < 1e5 for (R/Q)=118 Ohm.
- Dipole modes (SOM):

  $V_{kickSOM}$ < 0.01V_{kick} = 37.5 keV for Δy=0.5 mm.

  Q_{load} < 1e8.
- Dipole modes (HOM):

  Q_{load} < 5e8 for *(R/Q)* = 6 Ohm (*f*=529 MHz).

Note that the estimations for the parasitic modes were made for the worst case of the resonance excitation because the beam spectrum contains side bands spaced by 1 MHz. Thus, utilization of parasitic mode dampers may be considered. The entire structure is shown in Figure 9.

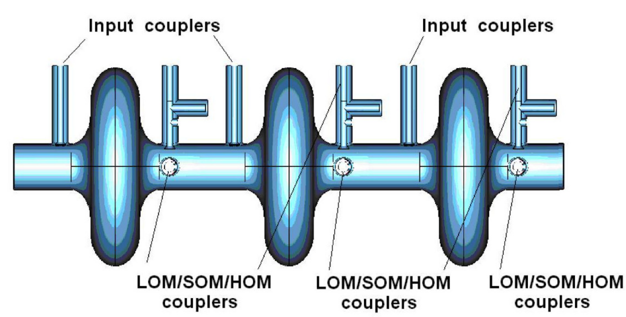

Figure 9: RF structure of the beam splitter.

An entire length of the structure is about 3.5 m. Additional RF separators allow simultaneous operation for more than 3 users.

CONCLUSION

Initial requirements for an RF separator have been identified. A potential solution using a CW SC RF cavity in a transverse deflecting mode proposed.

REFERENCES

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

[2] K.Hosoyama, *et al*, SRF2007, MO405.