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BEAM TEST OF A HIGH PRESSURE CAVITY FOR A MUON COLLIDER*

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Abstract

To demonstrate the feasibility of a high pressure RF cavity for use in the cooling channel of a muon collider, an experimental setup that utilizes 400-MeV Fermilab linac proton beam has been developed. In this paper, we describe the beam diagnostics and the collimator system for the experiment, and report the initial results of the beam commissioning. The transient response of the cavity to the beam is measured by the electric and magnetic pickup probes, and the beam-gas interaction is monitored by the optical diagnostic system composed of a spectrometer and two PMTs.

INTRODUCTION

Ionization cooling channel for a muon collider requires the operation of an RF cavity in a strong magnetic field. Since the maximum field gradient of a pressurized cavity is not affected by the external magnetic field (due to Paschen's law), the High Pressure RF (HPRF) cavity concept can provide a very compact and effective solution for the cooling channel design. One possible problem expected in the HPRF cavity is, however, the dissipation of a significant RF power through the electrons generated from the beam-induced ionization of a background gas [1]. Therefore, a conclusive demonstration of the feasibility of the HPRF cavity is a critical step in the muon collider R&D program. The experimental setup reported in this paper includes the 400-MeV proton beamline from the Fermilab linac, and the HPRF cavity apparatus sitting inside the solenoidal magnet of the MuCool Test Area (MTA). Since $dE/dx \approx 4\ \mathrm{MeVcm^2/g}$ for a minimum ionizing muon, we note that the typical linac intensity of $\sim 6 \times 10^{12}$ protons/pulse with $dE/dx \approx 10\ \mathrm{MeVcm^2/g}$ inside the cavity, is equivalent to $\sim 1.5 \times 10^{13}$ minimum ionizing muons.

DESCRIPTION OF THE BEAMLINE

The MTA beam is extracted directly from the Fermilab linac via two pulsed C-magnets (Fig. 1), which are capable of kicking the full linac pulse ($\sim 1.6 \times 10^{13}$ protons/pulse) at 15 Hz rep. rate . Once extracted, the beam is steered up to the shield wall through the five cooling ring dipoles (CRD). To provide an accurate information of the transverse emittance, three multiwire profile monitors are installed in the 10 m-long dispersion-suppressed straight section of the beamlin,e which penetrates into the 12 ft-long concrete shielding blocks that separate the experimental hall from the linac. A quadrupole triplet focuses the beam to a small waist (typically $\sigma_{95\%} < 5$ mm), which is located at the midpoint of the drift section. To get good accuracy, one profile monitor is normally placed at the beam waist. During the emittance measurements, the beam is dumped into a special beam absorber which is located at $\sim$ 5-m upstream from the main experimental target.

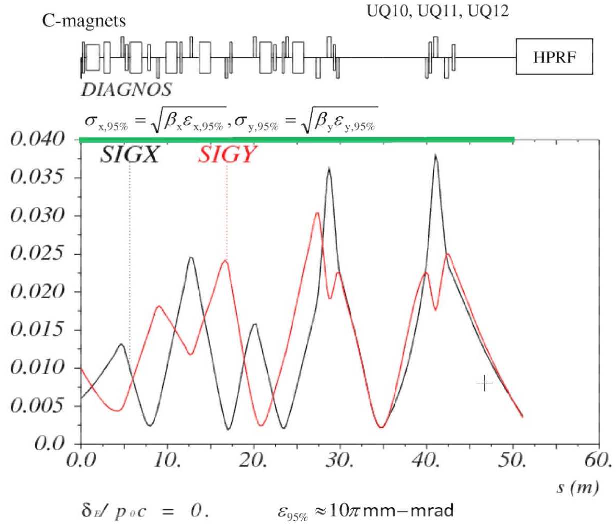

Figure 1: Plots of the 95% beam sizes along the beamline, which are calculated from the MAD code.

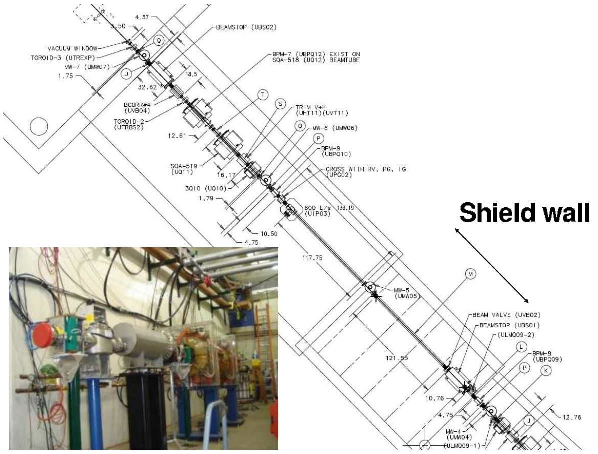

Figure 2: A photograph and a drawing of the MTA beamline showing the various focusing elements and beam diagnostics [2].

In the MTA hall, there is another set of the quadrupole

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triplet (UQ10, UQ11, and UQ12) which focuses the beam to the HPRF cavity. By changing the quadrupole coefficient of the each magnet independently, we can adjust the spot size at the target. It should be noted that the $\sim$ 50 m-long beamline has an overall vertical inclination of about 1.5 degrees. Therefore, a final vertical bending magnet is required to level the beam off before hitting the target. In addition to the two multiwires (MW 5&6) used for the emittance measurements, there are several more beam diagnostics installed in the MTA hall, which include the two beam toroids, two BPMs, three beam-loss monitors (BLMs), and an additional multiwire near the vacuum window (see Fig. 2). In particular, the last toroid in the beamline (shown as a green rectangular box in Fig. 2) will provide the most useful information on the beam status. The currently installed PEARSON Model 301X current monitor does not have enough sensitivity (0.01 V/A) for the typical linac beam intensity of $I_b \approx 32$ mA, and thus, will be replaced by PEARSON Model 3100, which has a sensitivity of 1.0 V/A. Moreover, to minimize the beam propagation in open air, an additional 4-m long beampipe will be added to the end of the present beamline, while the vacuum window (made of titanium) will be moved to $\sim$ 1-m upstream from the target.

COLLIMATOR AND CAVITY ASSEMBLY

For the precise measurements of the loading effects in the HPRF cavity, it is necessary to reduce the beam intensity by about a factor of 10 [3]. Too much beam will essentially short the cavity, making any measurements of the transient effects impossible. Indeed, we can control the beam intensity that goes through the cavity by putting a collimator. The collimator is placed in front of the cavity, and the amount of the beam through the cavity can be varied by changing the spot size of the beam itself and the hole size of the collimator. The beam spot size is easily adjusted by a set of the quadrupole triplet in the MTA beamline, and the collimator is designed in such a way that the hole size (1, 2, and 3 mm in radius) can be changed through several easy steps. The collimator is composed of two 6-inch diameter cylindrical pieces of steel that are arranged to sit inside the support system that in turn sits on the two parallel rails (see Fig. 3). The support system has several set screws for accurate alignments. The front cylinder is 10 cm thick and has a 1-cm radius hole in the center. This front piece will indeed catch the back splash from the actual collimator behind. The second piece is 20 cm thick and has a hole in the center that does the actual collimation. Moreover, there will be a hook structure welded on each of these pieces so that they can be easily lifted out and handled remotely. Since some of the full-energy protons may pass through the cavity, it is necessary to have a beam stop behind the cavity. The beam stop is essentially a 6-inch diameter cylindrical piece of steel, but needs to be modified to accommodate a coaxial pipe that feeds the RF power from the waveguide. To minimize further scattering of the beam in the cavity wall and the electrode, the cavity will be modified by removing unnecessary materials along the beam path.

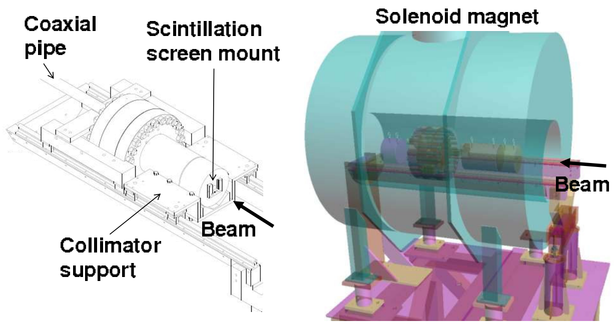

Figure 3: A CAD drawing of the collimator-cavity assembly and a 3D illustration of its installation inside the magnet (courtesy of R. Stewart).

Since no electrically-powered beam diagnostics are allowed within 15-ft from the HPRF cavity (due to the hydrogen safety), a scintillation screen is planned to be used for aligning the beam to the collimator center (see the 4 mm$\times$4 mm screen mount indicated in Fig. 3). We choose to use a thin plate (1 mm) of Chromox, which is fabricated from $\mathrm{Al_2O_3}$ powder with a Cr doping. The scintillation is made due to the Cr activator, and the light emitted is red (> 600 nm) with a decay time of $\sim$ 100 ms. The Chromox screen is known as one of the most widely used screens in proton machines [4], because of its mechanical robustness, reasonable sensitivity and spatial resolution ($\sim$ 100 μm), and fairly long lifetime. To detect the light intensity using a CCD camera located 15-ft away from the screen, we adopt a telephoto lens with a focal length of 200 mm. Moreover, to reduce the background light, a red color filter is mounted on the lens.

EXPERIMENTAL PLAN

The main diagnostics for the beam test will be the RF signals, such as the forward and reflected power signals, and the electric and magnetic pickup signals. To reduce the spurious reflections in the RF signals, a ciculator with a matched load will be inserted in the waveguide. To synchronize the beam with the RF, the main trigger for the klystron has recently been changed from its own standalone clock to the 15 Hz linac clock (LCLK). To trigger the various DAQ systems for the beam test, a special clock event, MOSEST, has been implemented, which is a 3 V TTL pulse with an adjustable delay with respect to the clock event 0A (linac study beam cycle) (see Fig. 4). Figure 5 shows an initial test result of the timing during the beam commissioning. We confirmed that when the

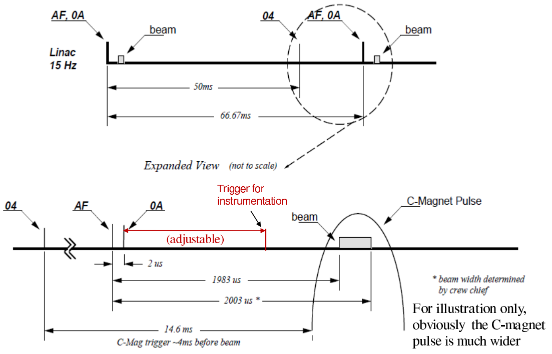

Figure 4: A diagram for the MTA timing with a new MTA instrumentation trigger implemented (courtesy of M. Kucera). Note that the C-magnets are triggered by the event 04 (MTA beam cycle) of the previous linac pulse.

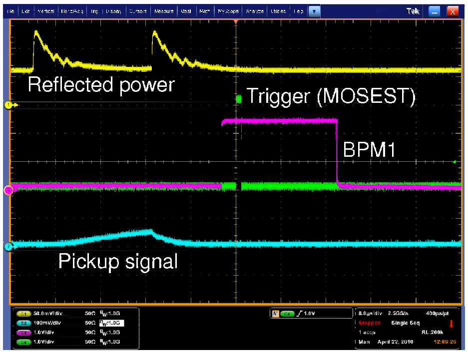

Figure 5: A screen shot of the fast scope showing the reflected power and pickup signal from the cavity, MTA instrumentation trigger, and BPM signal.

MOSEST trigger (or equivalently 0A) is issued, the beam is extracted from the linac and gives a finite signal on the first BPM of the beamline, which is located next to the C-magnets. In the actual beam test, of course, the delays will be adjusted so that the $\sim 20\ \mu$s beam pulse arrives when the RF amplitude is maximum in the cavity. Since the resonance frequency of the HPRF cavity depends on the gas pressure, and thus generally differs from the linac klystron frequency, the synchronous phase cannot be kept constant during the beam-cavity interaction.

In addition to the RF signals, the optical signals may provide some useful information on the molecular processes such as

$$\begin{array}{rcl} \mathrm{p} & + & \mathrm{H_2} \rightarrow \mathrm{H^*} + \mathrm{H^+} + \mathrm{e^-} + \mathrm{p}, \\ \mathrm{e^-} & + & \mathrm{H_2} \rightarrow \mathrm{H^*} + \mathrm{H} + \mathrm{e^-},\ \text{or}\ \mathrm{H_2^*} + \mathrm{e^-}, \\ \mathrm{e^-} & + & \mathrm{H_2^+} \rightarrow \mathrm{H^*} + \mathrm{H}. \end{array}$$

Two pressure-sealed optical ports are made in the cavity for this purpose. The light is collected and guided by the 1-mm diameter multimode optical fiber, and detected by the PMT either directly or through the spectrometer (HORIBA Micro HR, 150/600 grooves/mm). The PMTs used for this experiment (Hamamatsu H5783) have a rise time of ~ 0.78 nsec, and therefore allows us to resolve any periodic light emission associated with the 5-nsec bunch spacing.

The main scanning parameters for the beam test include the field gradient (E_0), gas pressure (p), and beam intensity. The beam intensity determines the electron generation rate, whereas the ratio E_0/p determines the equilibrium electron temperature T_e, which in turn affects the recombination and attachment rates for the electron evolution. To observe the recovery of the pickup signal after the beam passes through the cavity, it is recommended to use rather a long ($> 50\ \mu$m) RF pulse. Note that, however, the pulse length of the beam itself cannot be easily changed due to some technical limitations in the LLRF system.

To check the beam alignment with respect to the collimator hole, and to measure the actual intensity of the collimated beam that goes into the cavity, the initial suite of the experiments may be performed with replacing the HPRF cavity by a Faraday cup. The reproducibility of the collimated beam can also be verified in this setup.

The ultimate operational limit for the beam test is set by the radiation safety. To keep the residual dose rate at 1-ft away from the source less than 100 mrem/hr, the rep. rate is limited up to 1 pulse/min [5]. The total number of the beam pulses allowed per day and the required cooling time will be determined after a more detailed radiation safety analysis.

CONCLUSIONS

To demonstrate the feasibility of a high pressure RF cavity for use in the cooling channel of a muon collider, an experimental setup that utilizes 400-MeV Fermilab linac proton beam has recently been developed. By systematically measuring various responses from the beam-gas interactions in the cavity, it is expected that we can get a better understanding of the beam-induced electron loading effects, and come up with a practical mitigation method of them.

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