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FIELD EMISSION STUDY OF RF CAVITY IN STATIC MAGNETIC FIELD*

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Abstract

The RF cavity performance in solenoid magnetic field is crucial for the muon ionization cooling. Previous experiments have shown that the strong external magnetic field can significantly lower the maximum achievable RF voltage in the cavity. The mechanism of this performance degradation has been studied both analytically and experimentally, but so far no conclusive cause has been determined yet. In this paper, we propose an experiment to study the effect of a static B field on the field emission in the RF cavity, which hasn't been investigated before, and which can contribute to the cavity performance degradation in the solenoid field.

INTRODUCTION

The muon ionization cooling scheme requires operating RF cavity up to tens of MV/m in the solenoid field up to tens of Tesla [1]. Previous experiments have shown that the external static magnetic field can significantly lower the maximum achievable RF voltage in the cavity [2]. Different mechanisms have been proposed to explain this cavity performance degradation [3,4], and a series of experimental tests have been carried out at Mucool Test Area (MTA) at Fermilab. A modular cavity [5], which is designed specifically for the study of RF breakdown in solenoid field, will be studied at MTA systematically and extensively.

Though the specific mechanisms are different in different models, it is widely accepted that the field emission electrons play an important role in the RF breakdown. The field emission of different materials and surface conditions have been studied for RF breakdown and electron gun performance. However, no such study has been carried out in strong static magnetic field, at least not to the author's knowledge. Though the modular cavity test plan at MTA is systematical and extensive, with sophisticate diagnosis instrumentations, it emphasizes on the cavity performance as a whole and the modular cavity is not designed for the accurate field emission measurement.

A more suitable platform to carry out this study is an electron RF gun. The majority of the field emission in the RF gun is around the cathode area and the beamline after the gun is usually equipped with beam current, emittance and energy diagnosis. The major modification to the beamline will be to add an extra magnet to increase the B field at the cathode area.

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CONCEPTUAL DESIGN

AWA Photoncathode RF Gun

The RF gun we use for this study is the photocathode RF gun on the "Witness Beamline" at Argonne Wakefield Accelerator (AWA) Facility [6], as shown in Figure 1. It is a 1.3 GHz one-and-a-half cell gun, with gradient on the cathode up to 80 MV/m.

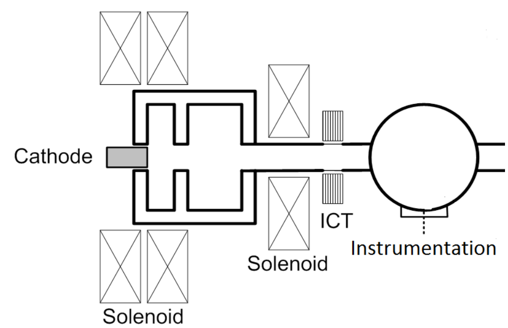

Figure 1: AWA RF gun.

Around the RF gun, there are two bucking solenoid coils near the cathode and one main coil farther away. The bucking solenoid runs up to about 0.14 T each and the main coil fringe field near cathode is negligible, thus the maximum B field on the cathode with current setting is 0.27 T, which is far below the magnetic field in the muon cooling channel. In the future, we need to install new magnets to increase the B field on the cathode.

Immediate after the RF gun, there is an Integrated Current Transformer (ICT) to measure the beam current. Further down the beamline, at the instrumentation insertion port, one can insert a Faraday Cup (FC) to measure the dark current. These diagnosis will be used for the field emission electron measurement.

Measurement of Dark Current

The average dark current based on Fowler-Nordheim theory is [7]:

$$\bar{I}_F = \frac{5.7\times 10^{-12}\times 10^{4.52\phi^{-0.5}} A_e(\beta E_0)^{2.5}}{\phi^{1.75}} \times \exp\left(-\frac{6.53\times 10^9 \phi^{1.5}}{\beta E_0}\right),$$

where ϕ is the cathode work function, A_e the effective emitting area, β the field enhancement factor and E_0 the peak RF E field. A Faraday cup can be placed at the downstream instrumentation insertion port to measure the dark current. We will change the external magnetic field to see if there is any change in the FC signal.

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The main challenge is the beam focusing/defocusing effect from the solenoid field. Since the electrons are emitted from cathode, the gap around the cathode and other high field place in the gun, with a wide relative momentum span, the portion of electrons which can be collected by the FC, which is about 1 meter downstream from the cathode, depends on the strength of the solenoid field. How the change of the external solenoid field changes the beam transportation, thus affects the interpretation of FC data, needs to be examined carefully with electron tracking simulation.

Measurement of Schottky-enabled Photonemission

Another method is to measure the Schottky-enabled photoemission [8]. The kinetic energy of the emitted photoelectron is:

$$E_{kin} = h\nu - \phi + \alpha\sqrt{\beta E},$$

where $h\nu$ is the photon energy, $\alpha = \sqrt{4\pi\epsilon e^3}$ a constant and E the instantaneous RF field gradient on the cathode. When $h\nu$ is smaller than ϕ, the condition for photoelectron emission is:

$$\alpha\sqrt{\beta E} > \phi - h\nu.$$

Thus by measuring the threshold RF gradient/phase, we can derive the field enhancement β, which affects the field emission. The measurement will be carried out under different solenoid field levels.

By choosing the proper photon energy, RF magnitude and RF phase of laser beam, we should be able to separate the dark current and photonemission current in the time domain. Compared with the previous method, the change of the solenoid field should have much smaller effect on the transportation of the photoelectron beam, since the much smaller transverse and longitudinal emittance.

FIRST TEST RUN

The first test run is a direct measurement of dark current without laser beam, similar to an experiment carried out at DESY [9]. The magnetic field on cathode is provided by the bucking coils up to about 2200 Gauss, corresponding to 450 A current in the coil. Instead of a Faraday cup, a YAG screen is placed about 1 m downstream of the cathode. A PMT detects the X-ray signal when the dark current hits the YAG screen, as shown in Figure 2. The RF gradient in the RF gun is ramped from about 42 MV/m to 62 MV/m.

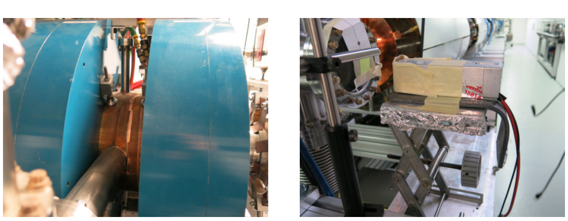

Figure 2: The left picture shows the bucking coils and main coil around the RF gun. The right picture shows the PMT outside the instrumentation insertion port.

First, the main coil is kept at 0 A and the bucking coils are scanned from 0 to 450 A, with 50 A interval. The PMT reading results are shown in Figure 3.

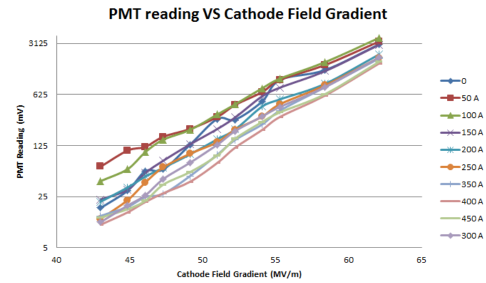

Figure 3: Scan of Bucking Coil Field Strength.

Then, to see how much the main coil Magnetic field will affect the PMT reading, we keep the RF gradient at 52 MV/m and the bucking coil at 250 A, and scan the main coil from 0 to 250 A. The PMT reading result is shown in Figure 4.

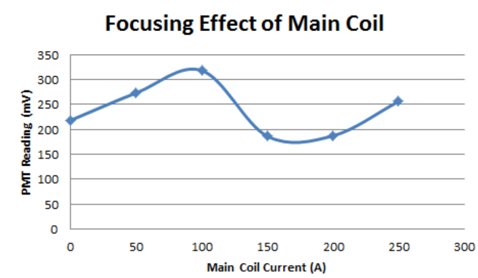

Figure 4: Scan of Main Coil Field Strength.

Due to the change of focusing as we change the solenoid field, the transportation of the dark current from the cathode to the insertion port is not fully understood. More detailed simulation needs to be carried out. Also the PMT signal is not a direct measurement of the electron beam but the X-ray from its bombardment on the YAG screen. The relation between the PMT signal and dark current is not fully calibrated. In the future, we also plan to measure the current directly with a Faraday cup.

FUTURE PLAN

Based on the purpose of our experiment and the experience from the initial test, here is the plan for the future work:

- A simulation model should be built for the current experiment setup. The model should be able to track the electron transportation and show how the magnetic field setting affects the number of electrons arriving at the instrumentation insertion port. The simulation results should be analyzed with the experiment data of the first test run.
- For the next run, without any major hardware effort and beamline alternation, we would like to carry out a Schottky-enabled photoemission test.

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- The current magnetic field at the cathode is too small compared to the solenoid field in the muon cooling channel. We need to prepare and install new magnet to increase the cathode magnetic field up to at least a few Tesla. Considering the power and cooling requirement, it could be a pulsed magnet as long as the pulse is longer than the RF pulse.

SUMMARY

An experiment to study the field emission in RF cavity with strong external magnetic field has been proposed. A RF gun is a good platform for this study, due to the high RF field around the cathode area and the sophisticate beam diagnosis of the cathode beam. The major hardware effort would be the installation of an extra magnet to increase the B field around the cathode. A first test run has been carried out at Argonne AWA. More simulation work on the beam transportation with varying solenoid fields needs to be carried out to interpret the data from this run. In the future, we plan to carry out a Schottky-enabled photonemission experiment. Depending on the available resource, an extra magnet will be installed to increase the B field around the cathode.

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