DETAILED EXPERIMENTAL CHARACTERIZATION OF AN IONIZATION PROFILE MONITOR

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Abstract

In the frame of the International Fusion Material Irradiation Facility (IFMIF), a prototype for a non-interceptive transverse beam profile monitor based on residual gas ionization (IPM) has been built and characterized in detail. We present results of test measurements performed at GSI Darmstadt with pulsed Ca^{10+}, Xe^{21+}, and U^{28+} beams of up to 1.6 mA at 5 MeV/u and at CEA Saclay with 80 keV protons in a cw beam of up to 10 mA. The effects of N_2, and different rare gases in the pressure range from $4 \cdot 10^{-7}$ mbar to $5 \cdot 10^{-4}$ mbar have been investigated. The signal was read out by different electronic cards, based on linear and logarithmic amplifiers as well as on charge integration. Furthermore the extraction voltage of the IPM field-box was varied between 0.5 and 5 kV. Beam profiles were investigated with respect to signal intensity and profile shape and were compared to a SEM-grid (Secondary Electron EMission) and a BIF-monitor (Beam Induced Fluorescence). Profiles of all monitors match nicely for the residual gases with differences in beam width well below 5 %. Additional tests on the characteristics of the IPM have been performed and will be presented as well.

INTRODUCTION

The *International Fusion Material Irradiation Facility (IFMIF)* accelerator will serve as intense neutron source by accelerating two 125 mA *continuous wave (cw)* deuteron beams up to 40 MeV and having them collide with a liquid lithium target. In the resulting nuclear reactions, neutrons are created. The IFMIF-*EVEDA (Engineering Validation Engineering Design Activities)* will be a prototype of similar beam characteristics, but limited to a single 125 mA cw deuterium beam of 9 MeV [1].

A major challenge resulting from such beam conditions is the very high beam current at rather low energies that makes non-interceptive diagnostics mandatory and requires a very compact accelerator design leaving only little room for beam diagnostics. An additional challenge is the increased radiation level due to the lithium target / the beam dump which makes high demands on the instrumentation in terms of radiation tolerance.

The development and experimental characterization of a prototype for an *Ionization Profile Monitor (IPM)* for the IFMIF- and the IFMIF-EVEDA – accelerator, already described by Marroncle et al. [2], was performed at CEA Saclay, France, and GSI, Germany, and will be presented in this contribution.

When the accelerator beam passes through the residual gas, it will partially ionize the residual gas present in the beam pipe. By applying an electric field, one can extract the ionization products and thereby derive the beam profile. For this technique, it is of utmost importance to have the ionization current keep its profile during the drift to the read-out plate. This requires the extraction field to be highly uniform. In addition, a magnetic guidance field is commonly applied to confine electrons along their drift pass to counteract space-charge effects from the beam, for instance. Due to a lack of space however, we had to abstain from a magnetic field guidance for the IFMIF-EVEDA IPM and will therefore collect only ions and no electrons.

IPM DESIGN

The ions will be collected on 32 strips with 1.25 mm pitch, thereby covering an active region of 40 mm. The electric field is applied by a field box with six degraders on each side, a high-voltage plate on the bottom, and the read-out strip on top. In front of the strips, a slit of variable aperture is mounted to restrict the ion collection to the IPM center. The read-out strips are set on ground potential to achieve an improved data acquisition. Such an asymmetric voltage alignment raises challenges for the field box design.

The IPM field box was therefore carefully optimized according to simulations of the electric extraction field performed by Lorentz-E [3]. Correction electrodes in form of wires have been mounted outside of the field box and voltages were adjusted. The resulting potentials in the central plane of the field box are given in Fig. 1. Taking the horizontal electric field component in this plane as a measure, the electric field was found to be uniform within 3 %.

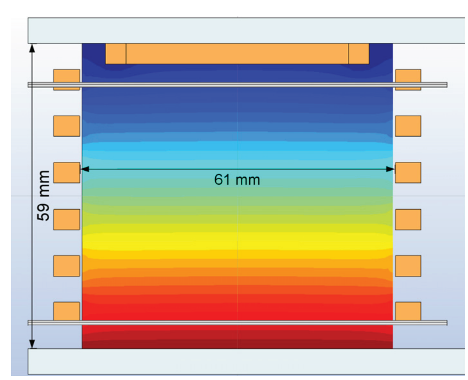

Figure 1: Electric potential in the central plane of the IPM field box.

TEST AT GSI

The IPM prototype has been tested at GSI, Germany, during two campaigns in May and November 2010. It was mounted at the X2 branch which is designated for diagnostics development and is equipped with beam profile monitors for comparison measurements as well as a gas inlet system which allows for an easy adjustment of the IPM output signal. The IPM was mounted on a stepper motor to move it stepwise perpendicular to the beam. During the test measurements three different beam types have been available, Ca^{10+}, Xe^{21+}, and U^{28+} of up to 1.6 mA at 5 MeV/u.

Front-End Electronics

During the test, three conceptually different electronic cards have been available, based on linear transimpedance amplifiers, logarithmic amplifiers, and charge integration. The linear and the logarithmic card give multiplexed profiles every 2 μs. The integration time of the charge integrating card can be chosen between 18 μs and 350 ms. For the final IPM, probably integrating electronics will be used since they allow for an easy gain adjustment by varying the integration time and since high read-out frequencies will not be required.

Electric Field Uniformity

During the IPM design, we payed much attention to the electric field uniformity within the IPM field box. We have therefore tested the electric field uniformity by driving the IPM in 2 mm steps through the beam and plotting the profile center versus the IPM displacement. For a perfect field uniformity, a linear correlation with unitary slope is to be expected. The resulting plot is given in Fig. 2.

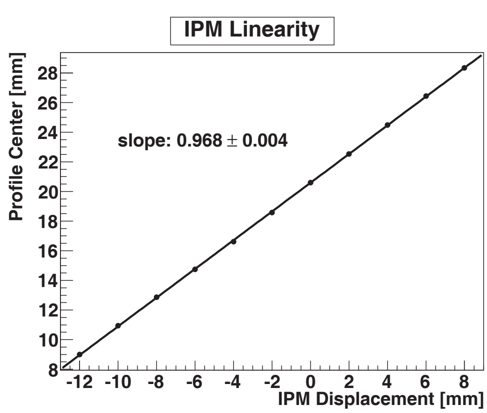

Figure 2: Test of the electric field uniformity.

The slope of the linear fit is in good agreement with the unitary slope expected. One can conclude that the electric field appears to be highly uniform as it was expected from simulations.

Extraction Field Effect

To reduce effects like space charge that result in profile distortions, the extraction voltage is commonly chosen to be as high as possible. We have taken profiles of a 1 mA Xe^{21+} beam at various extraction voltages in different residual gases to estimate this effect. The standard deviation of the beam is plotted versus the extraction voltage in Fig. 3 for the four noble gases neon, argon, krypton, and xenon.

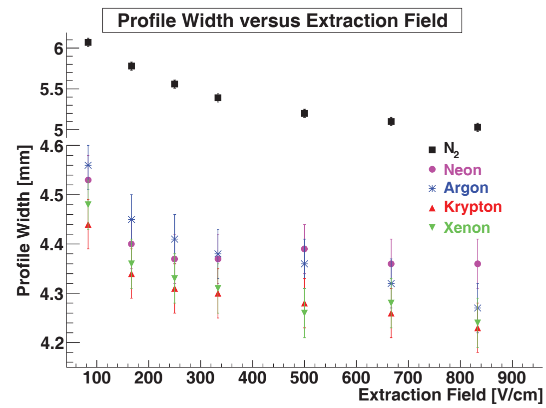

Figure 3: Measured IPM profile width versus extraction field in different residual gases.

During the measurement, the beam properties seem to have changed, so that the N_2 profiles are much broader than for the other gases. This effect was observed by the IPM as well as by the BIF.

For all gases, the profile width shrinks rapidly at low extraction fields. At higher fields, it approaches a constant value asymptotically. This effect can be interpreted as profile distortions due to initial ion velocities and beam - ion interaction. Since the ions as well as the beam are positively charged, these effects result in a profile broadening. For higher extraction fields strengths, the extraction field dominates any distortion effect and since the electric field is considered uniform, this constant can be identified as the correct beam width.

It is remarkable that the effect is far stronger for N_2 than for the noble gases. For N_2, the profile width shrinks by 20 %. This difference could be explained by the molecular state of the N_2 molecule in contrast to the atomic noble gases. N_2 molecules can break during the ionization process, resulting in charged N ions with increased kinetic energy. Additional tests with molecular residual gases are required to investigate this effect.

With increased extraction fields, the signal output of the IPM rises linearly, which cannot be explained by an increased ionization current as is does not not depend on the electric field. We suppose this to be due to an emission of secondary electrons on the level of the read-out strips during ion collection. The electrons are accelerated by the extraction field away from the strips which results in a net increase of the collected charge.

To test this hypothesis, we calculated the integral signal for different extraction voltages and residual gases, and determined the secondary electron emission yield required for such a signal amplification. The determined yields are higher than values commonly given in literature probably due to target treatments like etching and sputtering which was not performed for the IPM strips. The electron emission yields normalized on a mean value, however, are in good agreement with literature values for the all noble gases.

Profile Comparison

The position resolution of the IPM outside the profile center might differ significantly due to effects that lead to profile broadening without resulting in a profile shift, examples are space charge effects or initial ion velocities. The IPM profiles have therefore been compared with profiles acquired from a *Secondary Electron EMission (SEM)* grid and a *Beam Induced Fluorescence (BIF)* monitor, both provided by GSI.

For the profile comparison, a BIF monitor and the IPM have been used to take profiles in the same plane. During the measurement, the gas inlet system was used to vary the residual gas type and pressure. In the field box, as the highest applicable extraction voltage of 5000 V was applied, which corresponds to a mean electric field of 833 V/cm. As an example, profiles acquired by the IPM and the BIF of a 1 mA Xe^{21+} beam in 10^{-5} mbar nitrogen residual gas are presented in Fig. 4.

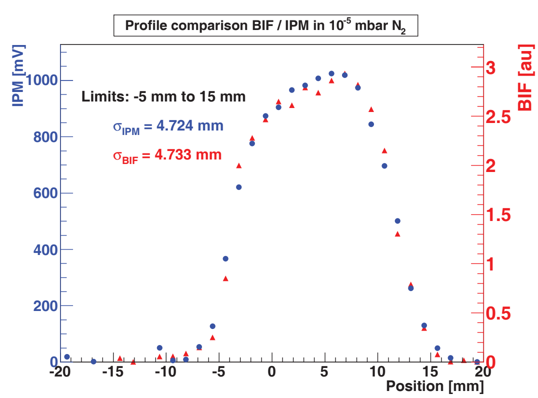

Figure 4: IPM and BIF profile comparison with a 1 mA Xe^{21+} beam.

Both profiles match nicely. The standard deviation of the profiles in the beam region from -5 mm to +15 mm has been calculated to be 4.72 mm for the IPM and 4.73 mm for the BIF. The deviation between IPM and BIF for other residual gases is commonly below 100 μm.

TEST AT IPHI

The source of the *Injecteur de Protons à Haute Intensité (IPHI)* is capable of delivering a pulsed or continuous proton beam of up to 100 mA at an energy of 95 keV. IPHI is thus capable of delivering a proton beam of similar characteristics as IFMIF in terms of current and duty cycle. However, the high ionization cross section resulting form the low beam energy and the lack of any beam collimation generate harsh conditions for the IPM since the field box is constantly irradiated by secondary particles.

Nonetheless, the IPM has been successfully tested for continuous high intensity beams and was capable to handle beams up to 10 mA cw current. For higher currents, the power supply started tripping due to an increased current consumption. We assume that secondary electrons created by the beam are attracted by the high voltage plate and thereby significantly increase the current load of the power supply.

This effect will be greatly reduced for the high-energetic and well-collimated beam of IFMIF and IFMIF-EVEDA. In addition, it is foreseen to increase the IPM aperture to the diameter of the beam pipe such that the beam pipe will act as a shielding for the IPM.

CONCLUSION

During the tests performed at GSI, the IPM was characterized in detail. We have found the electric extraction field to be highly uniform. By varying the extraction voltage, we have shown that at given beam conditions the electric field is strong enough to dominate the extraction process and that distortions from space charge and the like are minimal.

The IPM has been compared with a BIF monitor and a SEM-grid. Profiles of the different monitors match nicely. The spatial resolution of IPM is conclusively determined to be below 100 μm.

AT IPHI, we proved that the IPM can operate under high current cw beam condition. Due to the increased level of background at the IPHI source for higher beam currents, tests have been limited to 10 mA.

The final IPM has been designed based on the findings at GSI and IPHI and will be manufactured and tested at CEA Saclay in 2011.

ACKNOWLEDGEMENTS

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