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# Faraday cup for commissioning and quality assurance for proton pencil beam scanning beams at conventional and ultra-high dose rates.

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**Abstract**

Recently, proton therapy treatments delivered with ultra-high dose rates have been of high scientific interest, and the Faraday cup is a promising dosimetry tool for such experiments. Different institutes use different Faraday cup designs, and either a high voltage guard ring, or the combination of an electric and a magnetic field is employed to minimize the effect of secondary electrons. The authors first investigate these different approaches for beam energies of 70 MeV, 150 MeV, 230 MeV and 250 MeV, magnetic fields between 0 mT and 24 mT and voltages between -1000V to 1000V. When applying a magnetic field, the measured signal is independent of the guard ring voltage, indicating that this setting minimizes the effect of secondary electrons on the reading of the Faraday cup. Without magnetic field, applying the negative voltage however decreases the signal by an energy dependent factor up to 1.3% for the lowest energy tested and 0.4% for the highest energy, showing an energy dependent response. Next, the study demonstrates the application of the Faraday cup up to ultra-high dose rates. Faraday cup measurements with cyclotron currents up to 800nA (dose rates of up to approximately 1000 Gy/s) show that the Faraday cup is indeed dose rate independent. Then, the Faraday cup is applied to commission the primary gantry monitor for high dose rates. Finally, short-term reproducibility of the monitor calibration is quantified within single days, showing a standard deviation of 0.1% (one sigma). In conclusion, the Faraday cup is a promising, dose rate independent tool for dosimetry up to ultra-high dose rates. Caution is however necessary when using a Faraday cup without magnetic field, as a guard ring with high voltage alone can introduce an energy dependent signal offset.

**Key words:** Proton therapy, Ultra-high dose rate, Dosimetry, Faraday cup

## 1) Introduction

Due to the depth dose characteristics of charged particles, proton therapy allows for enhanced sparing of normal tissue compared to conventional radiation. Most conformal dose distributions are achieved with proton pencil beam scanning. Thorough commissioning and quality assurance of the proton gantry is important to guarantee repeatable and safe dose delivery to the patient. For each pencil beam, monitors in the gantry nozzle are used to control and check the deposited dose respectively (Pedroni et al., 2011). These monitors measure the pencil beam intensity in Monitor Units (MU, arbitrary unit), which need to be calibrated to the dose or the protons at iso-center. As such, two calibration methods exist (see for example (Goma et al., 2014, Palmans and Vatnitsky, 2016)): Calibration in terms of absolute dose measured with an ionization chamber (Dose/MU), and calibration in terms of proton fluence determined with a Faraday cup (Protons/MU). The Faraday cup (FC) measures the charge deposited by the proton beam, which is directly proportional to the number of delivered protons, and is an important device not only for commissioning of proton therapy facilities, but also for regular monitor quality assurance.

Recently, proton therapy treatments delivered at ultra-high dose rates are becoming of high scientific interest. Ultra-high proton dose rates could substantially decrease treatment times, and as such could help to mitigate the treatment of mobile tumours by allowing delivery of individual fields within a single breath-hold (Gorgisyan et al., 2017), (Emert et al., 2020). Furthermore, there is evidence that ultra-high dose rates could potentially lead to beneficial tissue sparing without compromising the tumor control due to the so-called FLASH effect. For electron treatments, this has been studied in detail in mice (Favaudon et al., 2014, Montay-Gruel et al., 2017), in mini-pig and cats (Vozenin et al., 2019), and recently a first patient has been treated at FLASH dose rates with electrons (Bourhis et al., 2019). Given their improved physical characteristics in comparison to electrons however, there is also a rapidly growing interest in FLASH therapy using protons (see for example treatment planning studies (van de Water et al., 2019, van Marlen et al., 2020)).

As such, high dose rate treatments are likely to become clinical reality in the next years, requiring developments in dosimetry and beam monitoring that can accurately deliver and measure such deliveries. In this context, the Faraday cup, the response of which is typically assumed to be independent of dose rate, is a promising tool to benchmark and characterize the dose rate dependence of beam monitors and field detectors. It has been employed by (Diffenderfer et al., 2020) for an IBA (Louvain-la-Neuve, Belgium) fixed beam line in a dedicated research room to validate dose rates measured with Markus chamber, and by (Darafsheh et al., 2020) to investigate FLASH dose rates for a Mevion Hyperscan facility.

The most simple Faraday cup design consists of a simple absorber block (the cup) which measures the proton charge (referred to as 'poor mans' Faraday cup in (Cascio and Gottschalk, 2009)). On the opposite side of the spectrum, more sophisticated FC's operate under vacuum and include both magnetic and electric fields to minimize the obfuscating effect of secondary particles (Verhey et al., 1979, Lin et al., 2009), mainly electrons, which can originate from the vacuum window or escape the cup. Alternatively, Faraday cups can also be operated with an electric field only (Grusell et al., 1995), still under vacuum conditions

The best settings of magnetic field and voltage have been investigated by (Verhey et al., 1979) for an 135 MeV proton beam for their specific FC. They concluded that "100%

efficiency" could be achieved with a 100G (10mT) magnetic field, with the measured signal then being independent of the applied voltage. On the other hand, they observed a 0.5% efficiency reduction with no magnetic field and a zero voltage bias, which remained also in the presence of negative voltages. In contrast, (Grusell et al., 1995) recommend to apply a -1000V voltage without magnetic field for a 174 MeV beam, and show a 4% signal reduction compared to no applied voltage. They estimated a possible systematic error of less than 0.3% when no magnetic field was applied, concluding that such a field was therefore unnecessary in their design. No measurements were performed to validate this assumption however. In addition, to prevent ionization of air molecules from influencing the measured charge, the Faraday cup is typically set under vacuum. Verhey et al (1979) measured the charge collected by the Faraday cup with a "spoilt vacuum", showing that the signal strongly depends on the applied Faraday cup voltage.

Table 1 summarizes different Faraday cups and their respective settings used at different centers. The table gives an overview on the geometric and material properties of the respective Faraday cups, and on the operating conditions. Additional design parameters which might influence the measured charge (shape of the absorber, the distance between the absorber and the guard) might be available in the reference literature given in the table. Following on the work of Verhey et al (1979), the PSI Faraday cup is currently operated at maximum magnetic and electric field to ensure that secondary electrons do not influence measured charges. To our knowledge however, Faraday cup settings have to date not been investigated for different proton beam energies spanning the whole therapeutic range (70MeV-230MeV). Furthermore, the influence of different magnetic field strengths on Faraday cup response for different proton energies has not been systematically quantified.

Taking into account the somehow contrasting literature summarized above, and considering the increased use of Faraday cups for ultra-high dose rate experiments, the authors are convinced that a more detailed analysis of the Faraday cup settings is of interest. As such, in this study, we first investigate the response of our Faraday Cup to changes in electric and magnetic field for multiple beam energies. We then demonstrate that the response of the FC is indeed dose rate independent, which is important for the renewed interest in high- and ultra-high proton dose-rate experiments. We finally present examples of clinical applications of a FC used for monitor calibration at high dose rates at our institute. Finally, we highlight the uncertainties when using such a device for monitor calibration, including measurement data taken over a 6 year time span.

1 Table 1: Faraday cups used at different centers.

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| Institute | Investigation | Block material, thickness, diameter | Entrance vacuum window | Operating conditions | Comment | Difference to ionization chamber measurements | Reference |
|---|---|---|---|---|---|---|---|
| TERA Collaboration (Italy) | 62 MeV<br>Voltage between -800V and + 800V, stable response for voltages below -150V | Aluminium, 3cm, 7cm | Mylar 0.05mm | Vacuum (10 -6 mbar)<br>No magnetic field<br>Guard ring (- 300V) | Measurements with non-homogeneous magnetic field were not reproducible | 3.4% | (Cambria et al., 1997) |
| Centre Antoine-Lacassagne (France) | 62 MeV<br>Voltage between -800V and 0V, stable response for voltages below -200V | Copper, 6cm, 6cm | Kapton 0.13mm | Vacuum (10-4 mbar)<br>No magnetic field<br>Guard ring ( -400V) | Agrees to the TERA FC within 1.5–3.6% | 5% | (Cambria et al., 1997) |
| University Hospital Uppsala and Karolinska Institute Stockholm, (Sweden) | 60 to 226 MeV<br>Voltage between -1500V and 0V, stable response for voltages below -1000V | Copper, 6cm, 12 cm | Steel, 0.5 +/- 0.05 mm | Vacuum (10-7 mbar)<br>No magnetic field<br>Guard ring (-1200V) | Magnetic field `considered unnecessary in the present design which is intended for use with high-energy protons` | 6% | (Grusell et al., 1995)<br>(Almhagen E and Grusell E 2020 Private Communication,see acknowledgements) |
| Francis H. Burr Proton Therapy Center, Boston (US) | ------------------- | Brass, 6.35cm, 12.57 cm | Kapton, 2 x 0.13mm and steel, 0.91mm | No vacuum, no magnetic field, no guard ring | "Poor Man's Faraday Cup", 1 to 5 percent difference to HCL FC. | 7% that could be reduced to 4% | (Cascio and Gottschalk, 2009)<br>(Clasie et al., 2012) |
| Harvard Cyclotron Laboratory (US) | 135 MeV, Voltage between -1000V and + 1000V Magnetic field measurements with 10mT - ground truth, and without magnetic field | Brass, 3.81cm, 10x12 cm | 0.076 mm Al foil | No magnetic field, no voltage | 0.5% lower signal at operating conditions compared to ground truth. | | (Verhey et al., 1979)<br>(Cascio and Gottschalk, 2009) |
| PSI (Switzerland) | ------------------- | Brass, 10cm, 12.7cm | Aluminium foil | Vacuum (10-5 mbar), magnetic field (24 mT), guard ring (-900 V) | | 3% | (Winterhalter et al., 2018), (Goma et al., 2014)<br>(Lin et al., 2009) |

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## 2) Materials and Methods

### *2.1) Faraday cup at PSI*

The Faraday cup used at PSI (Figure 1) is inspired by the design of (Verhey et al., 1979) and has been described in detail by (Lin et al., 2009). Protons are absorbed by a 10cm thick brass absorber (enough to stop protons up to 250 MeV), is sealed by an aluminium foil entrance window and operates under vacuum ($10^{-5}$mbar). The 12.7 cm diameter entrance window is wide enough to collect proton beams with varying widths over the whole energy range. A negatively charged guard ring (maximum negative voltage -1000V) and a magnetic field (24 mT) complete the design, with the latter overlapping both with the guard ring and the brass cup. The collected proton number is then simply determined by dividing the charge measured with an electrometer (dark current has been subtracted) by the proton elementary charge. For this study a Keithley electrometer (type 6517B) was used.

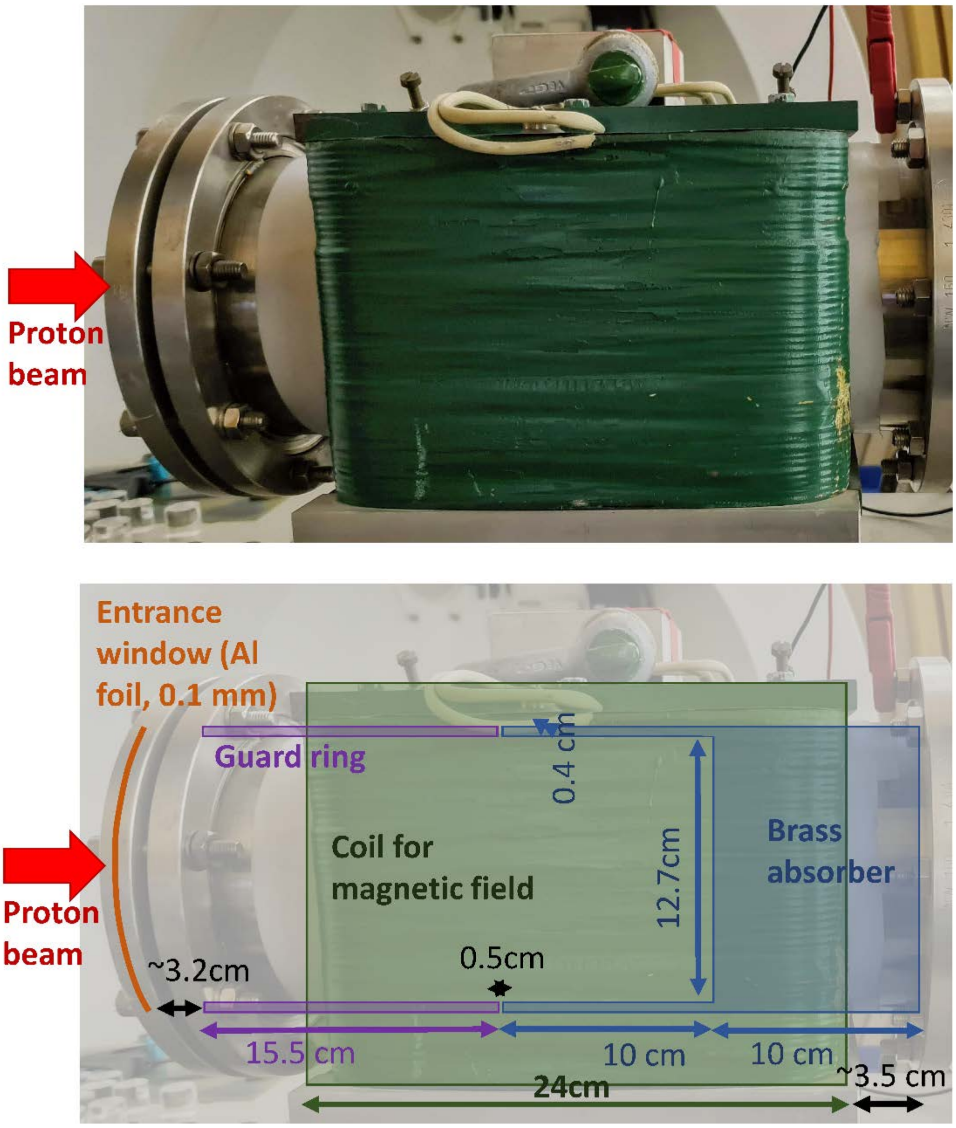


Figure1: PSI Faraday cup, photo (a) and photo overlaid with a schematic drawing of the individual components (b). The magnetic field lines between the coils are oriented vertically (orthogonal to the beam direction).

*2.2) Characterisation of the FC response for different magnetic and electric field strengths*

When using the Faraday cup, secondary electrons originating from the entrance window might contribute negatively to the measured proton charge, and electrons escaping from the brass absorber might add an positive bias to the measured proton charge. As such, a negatively charged guard ring between the vacuum window and the cup, as well as a magnetic field can be applied to minimize these contributions by averting secondary electrons from the entrance window and trapping electrons from the brass absorber.

To investigate the best settings of our Faraday cup, the FC response has been evaluated as a function of magnetic field (with no voltage), as well as for different applied voltages with both the magnet turned off and with maximum available magnetic field. Measurements were performed for four different energies, 250, 230, 150 and 70 MeV. The 250 MeV beam was delivered and measured in Gantry 1, which is described in detail in (Lin et al., 2009), while the remaining energies were tested in Gantry 2 (Safai et al., 2012). The magnetic field has been measured with a Gaussmeter 410 (LakeShore Cryotronics) in the space between the magnetic field coils and the Faraday cup housing. The Hall probe has been oriented manually, such that the measured magnetic field is maximal. The magnetic field vectors within the Faraday cup, which are created by the field coils, are oriented in the vertical direction, orthogonal to the proton propagation direction.

All results have been normalized to the values measured with the maximum magnetic field (24mT) and the maximum applied voltage of -1000V. Therefore, the outcomes presented are expected to be independent from the Gantry (1 or 2), in which the measurements took place.

*2.3) Clinical applications of the FC up to ultra-high dose rates.*

2.3.1) Dose rate independency

The dose rate independency of the Faraday cup has been demonstrated by analysing the proton current measured by the Faraday cup (ratio between the FC measured charge and delivery time recorded by the control system) for a 250 MeV beam for cyclotron currents up to 800nA (corresponding to dose rates up to 1000 Gy/s). Beam monitors used to measure the cyclotron current are ionization chambers suitable for high currents that give the instantaneous beam current (see Döllinger et al 2007). These measurements have been performed on a gantry (Gantry 1) that has now been taken out of clinical operation and is currently being re-purposed for FLASH and ultra-high dose rates experiments (see (Nesteruk, 2020)).

2.3.2) Dose rate response of a primary beam monitor

If dose rate independent, a Faraday cup is a useful device for independently assessing possible dose rate dependencies of other dosimetric devices. As such, during commissioning of a Varian ProBeam (VMS, Palo Alto, CA, US) gantry at our facility (Gantry 3), Faraday cup measurements have been performed to test the response of the primary dose monitor for dose rates of up to 30Gy/s at the monitor level. Energies of 70 MeV, 150 MeV and 210 MeV were investigated, while delivering 10MU/100MU/1000MU and varying the cyclotron current of 200nA-400nA (70MeV), 50nA-300nA (150MeV) and 25nA-200 nA (210 MeV), with the Faraday cup positioned at iso-centre.

### *2.4) Consistency of primary beam monitor calibration*

Finally, as FC measurements are a part of our periodic (3-yearly) Quality Assurance program, we have also been able to determine the consistency of primary beam monitor calibrations over a span of 6 years (2014-2020). The Faraday cup has previously been employed to calibrate the primary dose monitor of the PSI Gantry 2 (Pedroni et al., 2011) which controls the beam delivery and provides an input to the safety system. This monitor measures the deposited intensity in Monitor Units (MU, arbitrary unit). By measuring the number of protons with the Faraday cup for a fixed number of MU, a conversion curve MU to number of protons as a function of initial proton energy was obtained. This process has been already described elsewhere (Goma et al., 2014). As such, data taken on the PSI Gantry 2 in the energy range 70-230MeV and in 2014, 2017 and 2020 have been compared.

Repeated measurements performed on the same day in 2017 and 2020 have been used to assess the precision of the FC response.

## 3) Results

### *3.1) Characterisation of the FC response for varying magnetic and electric field strengths*

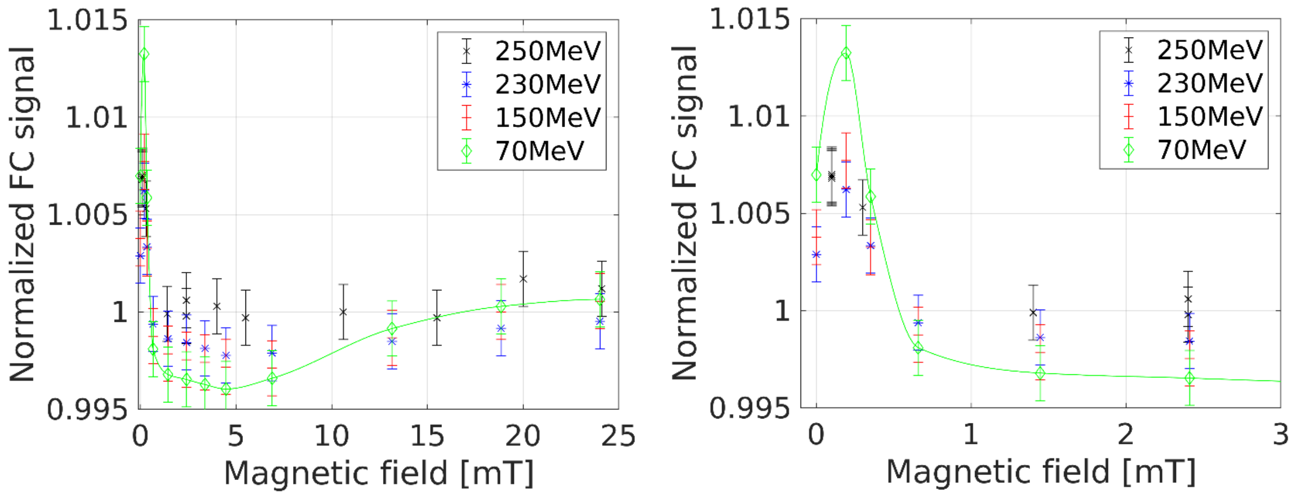


Figure 2: Faraday cup signal as a function of magnetic field with no applied voltage. The figure on the right focuses on the first few mT of the left figure. Proton numbers (per MU) have been normalized to the response at reference condition for each energy. 250 MeV has been measured in Gantry 1, 70MeV/150MeV/230 MeV in Gantry 2. A smooth line has been added to the 70MeV data.

Figure 2 depicts the response of the Faraday cup under different magnetic field settings without electric field, with the data normalized to the response with maximum magnetic and electric field for each energy (24mT/-1000V – referred to as the reference condition). The following behaviour is observed: as the magnetic field is decreased from maximum to about 5mT the response decreases slowly down by 0.4% for the lowest energy. Between 5mT and no magnetic field the behaviour is then inverted and the decrease is followed by a quick increase of the collected positive charge up to 1.3% higher compared to the reference value for the lowest energy. The magnitude of the behaviour appears to be energy dependent, with differences decreasing with increasing energy. For the 250 MeV beam the overall behaviour is less evident and masked by the accuracy of the measured data, with the exception of the increase around 0mT, which is still clearly visible. A plausible explanation of the observation can be formulated considering that backscattered secondary electrons leaving the brass cup tend to be less energetic than forward scattered secondaries leaving the vacuum window. When no magnetic field is applied the signal is contaminated by a surplus of positive charge since the negative charge (electrons) leaving the cup is not fully compensated by the incoming negative charge from the electrons of the vacuum window. The application of a small magnetic field (0.5- 1 mT) inverts this scenario by contaminating the signal with a surplus of negative charge since now the low-energy backscattered electrons are trapped while the more energetic electrons from the VW can still reach the cup. Only a much larger magnetic field, of the order of few 10mT can prevent all secondaries from the VW from reaching the cup. The second observation that the magnitude of the contamination decreases with increasing energy can be understood by the fact that the number of secondaries produced per incident proton is expected to decrease with increasing energy because the ionization density decreases. More in-depth investigation (including for example Monte Carlo techniques to analyse the energy, and behaviour, of secondary electrons) is necessary to further understand our observations.

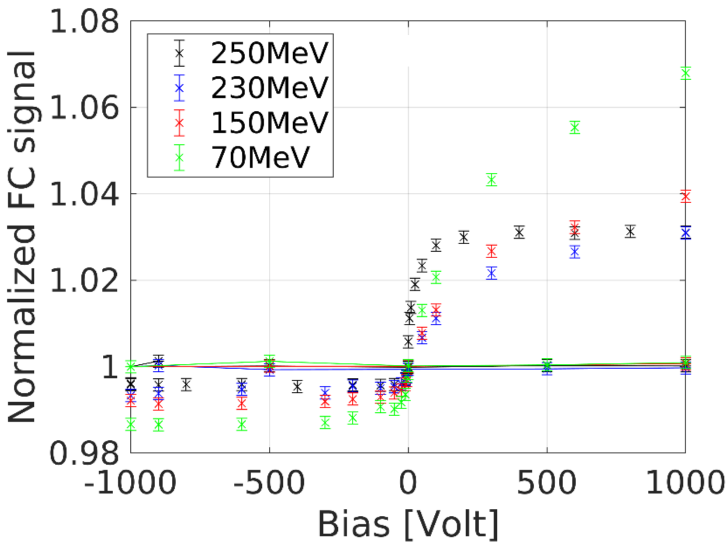


Figure 3: Faraday cup signal as a function of applied voltage when turning off the magnet (residual magnetic field between 0.3mT to 0.7mT) and with maximum magnetic field (line).

Figure 3 shows the response of the Faraday cup as a function of the strength of the electric field with either magnetic field turned off or maximum magnetic field. With a maximum magnetic field applied (24 mT), the measured signal was found to be independent of the applied voltage, in agreement with the results of (Verhey et al., 1979). Without magnetic field however, the applied voltage alone is insufficient to reach the reference response, with a signal that remains up to 1.3% lower than the reference. The residual contamination is likely caused by the fact that even the maximum applied electric field of -1000V is not sufficiently high to invert the trajectory of the most energetic forward directed secondary electrons originating from the VW. Interestingly, also in this case, the magnitude of the residual signal deficiency is dependent on the proton energy, with the smallest difference (0.4%) observed for the highest energy (250 MeV) and the largest difference (1.3%) for the lowest energy (70 MeV).

Again, the effect may be explained with the increased number of secondaries produced at lower energies.

### *3.2) Clinical applications of the FC up to ultra-high dose rates*

#### 3.2.1) FC dose rate independency

Figure 4 shows FC response as a function of beam current (a surrogate for dose rate) up to 800nA. Response is shown to be linear (residuals within 5%, figure 4b) over the complete range of current, corresponding to dose rates of up to approximately 1000Gy/s along the central axis, indicating that there is no dose rate dependence of the Faraday cup readout. In order to determine the transmission thorough the beamline for a given beam intensity, we recorded beam currents measured simultaneously by 2 intensity monitors (downstream and upstream) with a time resolution of 100 ms. The transmission varies between 84.5% for lower beam intensities and 86% for high beam intensities. This is due to the changes in the phase space of the beam extracted from the cyclotron. FC currents for high beam intensities with slightly higher transmission were normalized to the minimum transmission of 84.5% corresponding to the slope in figure 4a. The stability of cyclotron current during the charge collection was estimated to be always within 5%, with higher instabilities occurring at lower beam intensities. Therefore, a larger discrepancy between FC-derived and cyclotron currents (figure 4b) is observed for lower beam intensities. It should be pointed out however that this is an indirect test of the dose rate dependence of the Faraday cup, as it cannot be completely excluded that the monitor recording the cyclotron current might have exactly the same dose rate dependency as the Faraday cup. In practice however, this is highly unlikely, as these are two completely independent systems (ionization chamber versus Faraday cup).

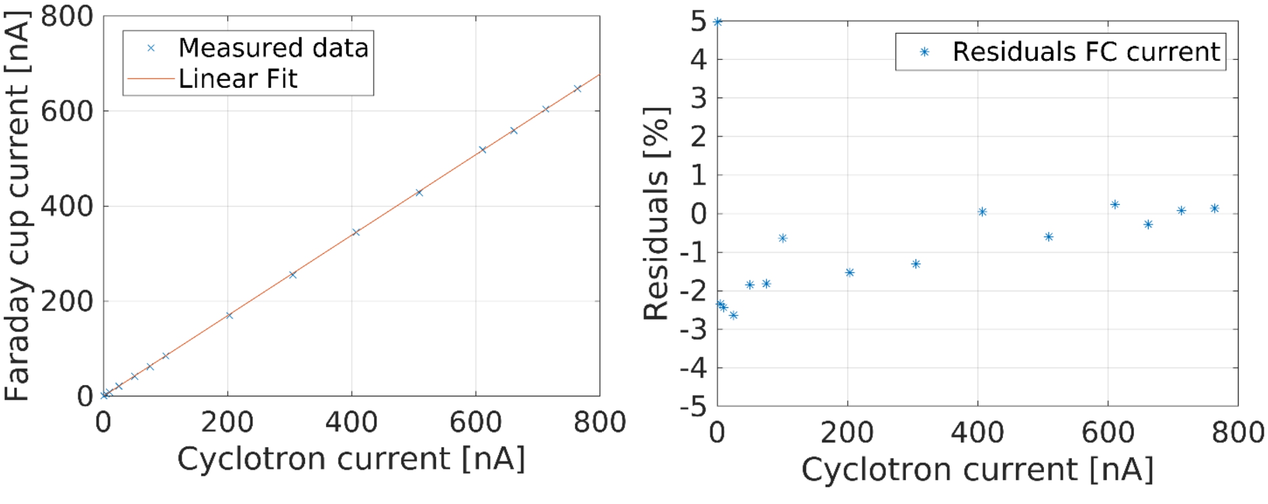


Figure 4: Faraday cup measured current (250MeV beam) as a function of cyclotron current (a) and residuals to a linear fit (b).

#### 3.2.2) Dose rate response of a primary beam monitor

The above described and characterised Faraday Cup has been used as part of the clinical commissioning of a Varian ProBeam gantry (Gantry 3) at our institute. It is estimated, that when the cyclotron is operated at its limit, the achievable maximum proton beam current at iso-centre in Gantry 3 is of the order of 5 nA. This corresponds to about 30 Gy/s in the beam monitor, which could result in high ion recombination effects. It was therefore decided to add a dedicated test on the response of the primary beam monitor, and the FC was then chosen as the instrument to benchmark the dose rate response of the monitor. Figure 5a shows the calibration p/MU of the primary beam monitor as determined with the FC as a function of the cyclotron current for different energies and level of requested MUs. For each energy and number of MU, the average p/MU is calculated and the difference to each data point plotted in Figure 5(b-d). As such, the dependency on the beam current can be considered as insignificant, since all values are below 1% and no trend can be recognized.

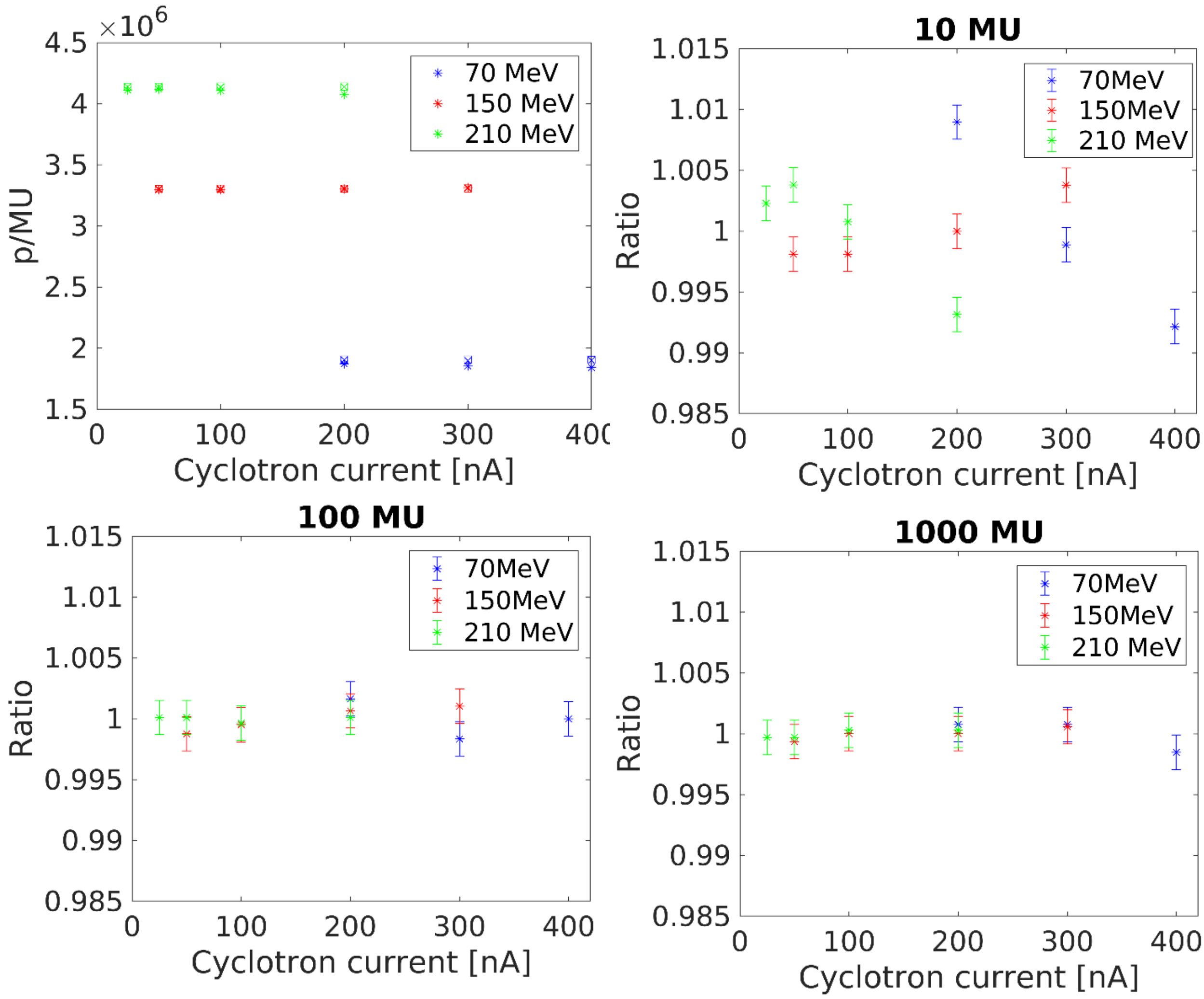


Figure 5: Monitor calibration for different energies and cyclotron currents (a), and ratio compared to the average when delivering 10MU (b), 100 MU (c), 1000 MU (d).

### *3.3) Consistency of primary beam monitor calibration*

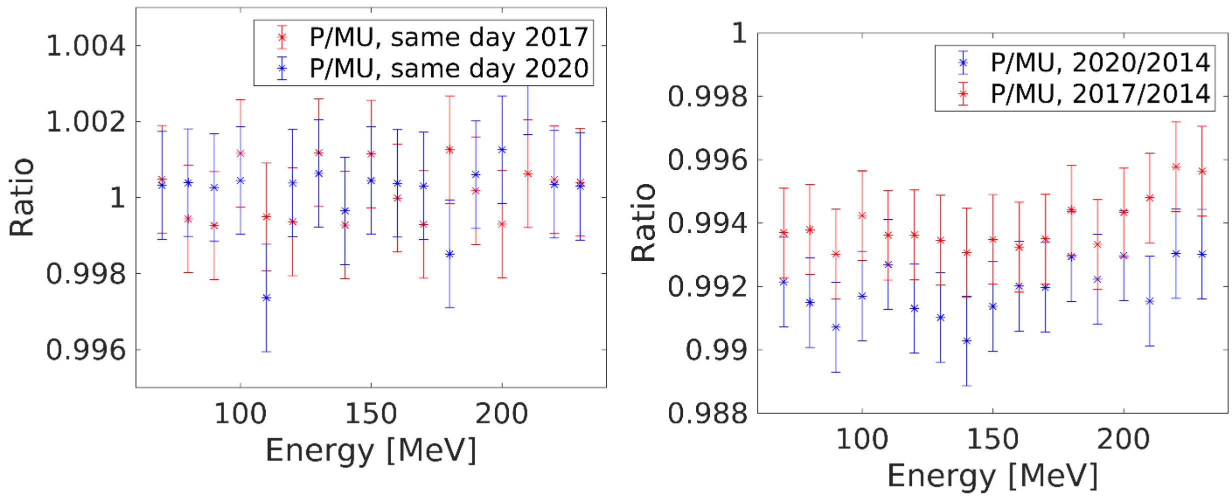


Figure 6: Reproducibility of p/MU measurements taken on the same day (a) and over multiple years (b).

Figure 6 shows FC response for measurements repeated on the same day in both 2017 and 2020, as well as a comparison of the reading of the device in 2014, 2017 and 2020. Faraday cup measured protons per monitor unit taken on the same day show a repeatability of the number of protons per MU of 0.1% (one sigma), with a maximal deviation of 0.3% (Figure 6a). Comparing quality assurance measurements of 2020, 2017 and 2014, results agree within 1% with a mean offset of -0.6%/-0.8% (2017/2020 compared to 2014, Figure 6b). Faraday cup measurements are therefore very well repeatable if acquired on the same day and our experienced showed that the reproducibility remains well under 1% (see also (Coray et al., 2002)). The difference of over 0.5% observed in the Faraday cup reading for the year 2017 and 2020 compared to 2014 is an indication that the output of Gantry 2 slightly drifted over the years. Results of the yearly reference dosimetry checks performed with calibrated ionization chambers show a similar drift over the same time period confirming a small change in the output of the treatment unit.

## 4) Discussion

Faraday cup measurements have been used for proton therapy for over 40 years (see for example (Verhey et al., 1979)). Not only are these employed for regular quality assurance, the Faraday cup is now being increasingly used with upcoming interest in high dose rate experiments. The best settings of the Faraday cup are important for any centre interested in these kinds of measurements, and different approaches, magnetic field and electric field (Lin et al., 2009) or electric field only (Grusell et al., 1995)) have been used in different centres.

In this work, we have investigated the dependence of Faraday cup response on applied magnetic and electric field. With a strong enough magnetic field, the signal does not depend on the applied voltage. This might be explained by the magnetic field “trapping” all electrons originating from the cup, and hindering all electrons from the vacuum window from reaching the cup. Without electric field however, but depending on the strength of the magnetic field, the reading of the FC could vary between +1.3% and -0.4% compared to the maximum magnetic field. The amplitude of the effect is dependent on the energy of the incident particle, with the largest differences observed for the lowest energy tested, i.e., 70 MeV. When applying only an electric field, without magnetic field (as it has been done by many institutes, see Table 1), even with a negative voltage of -1000V, the signal remains up to 1.3% lower than the reference readout. Again, the effect is energy dependent and is reduced to 0.4% for the highest energy of 250 MeV. The value reported by (Verhey et al., 1979) of 0.5% lower Faraday cup output without magnetic field and without applied voltage is within the range observed in this study, and was found for a magnetic field of 10mT for 135 MeV protons. Although Grusell et al. (1995) suggested that a magnetic field might not be necessary since such a field would correct a possible small systematic error of only 0.3%, the present study shows that the effect could be larger and exceed the 1% level depending on the energy of the incident particle, which is still small but not negligible. The energy dependency of the FC response is indeed noteworthy since a calibration of a beam line performed with a Faraday cup without magnetic field could be affected by energy dependent systematic errors. In conclusion, if an accuracy in FC measurements of below 1%-2% is required, the use of a magnetic field should be considered. However, such a Faraday cup tends to be quite bulky and heavy. As such, the choice of the right FC is a trade-off between accuracy and portability. It should be noted, that these results are specific for the investigated Faraday cup geometry. Different geometries may lead to different optimal settings, both for the magnetic field and electric field, and the magnitude of the observed effects could also be different. For instance, Grusell et al. (1995) observed a much higher change in response of about 4% compared to Verhey and our study. Nevertheless, as for all dosimetry equipment, our work demonstrates that each Faraday cup needs proper commissioning before its use.

The precision of successive FC measurements is of the order of 0.1% (one sigma, Figure 6). The error bars (one sigma) in figure 2, 3, 5 and 6 follow the propagation of such precision. As for figure 4, where results are shown for varying dose rates, the error in measured cyclotron current is expected to be dominant compared to the error in measured FC charge and timing. As this is difficult to estimate, we did not include any error bars in figure 4. This graph nevertheless qualitatively clearly shows the linearity between the two independent measurement devices, and as such the dose rate independency of the FC.

Adjusting and measuring the actual applied magnetic field is challenging task. In this FC, the magnetic field is controlled by adjusting the current applied to two coils. The strength of the field is characterized by hysteresis and depends on the ramping of the magnet. As such, depending on the history of the magnetisation and ramping sequence it could be that even when the magnetic field is turned off (no current through the coils) a residual magnetisation below 1mT is present. Such a residual field, between 0.3 to 0.7 mT, was observed for measurements performed in two different Gantries. Additionally, all magnetic field values are based on the magnetic field measurements in the space between the coil and the Faraday cup, and might as such differ from the magnetic field in the middle of the device.

Future work will investigate the exact contributions of secondaries either escaping from the cup or originating from the vacuum window to the measured charge, and the influence of different Faraday cup geometries and materials (for example of the entrance vacuum window). Additionally, simulations of the exact contributions of different secondaries (electrons/protons) are needed to determine which setting represents the optimal response, and to investigate whether the overlap of magnetic field and brass absorber influences the presented results.

Table 1 shows an overview on the differences between ionization chamber measurements, and FC based absolute dose verification, ranging between 3%-6% for different institutes. These differences might be caused by the ionization chamber, the theoretical model used to convert FC measured fluence to absolute dose, and the response of the FC. As such, the different values observed by different institutes might be partly explained by the different operating conditions of the respective FC.

Importantly, we have also demonstrated that the Faraday cup does not depend on the dose rate up to ultra-high dose rates of 1000 Gy/s. As such, the Faraday cup is a valuable tool for commissioning of monitors and field detectors up to ultra-high dose rates. Additionally, Faraday cups might not only be interesting for proton FLASH experiments, but might also be an interesting tool for other high-dose rate particle beams, for example electrons or heavier ions.

## 5) Conclusions

Using a magnetic field only, or using an electric and magnetic field combination, leads to an optimal Faraday cup response, for which the influence of secondary electrons is minimized. For the PSI Faraday cup geometry, no magnetic field and no electric field would cause a FC reading up to 1.3% higher compared to the response with maximum magnetic field, while using only a negative electric field would cause a FC reading 1.3% lower compared to the response with maximum magnetic field. In conclusion, this study shows that the Faraday cup is an effective tool for commissioning, calibration and quality assurance for proton pencil beam scanning monitors, which will be especially important for ultra-high dose rate experiments.

## 6) Acknowledgements

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