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Non-Interceptive Beam Current and Position Monitors for a Cyclotron Based Proton Therapy Facility

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Chapter 6: Summary and Outlook

6.1 Review: thesis objective

The thesis reports on the investigation of a non-interceptive beam diagnostic for measurements of beam current and beam position in the PROSCAN beamlines. The motivation to explore this possibility was to replace some of the ionization chambers (ICs), as they degrade the beam quality through multiple scattering. The principle of cavity resonance was chosen as the candidate to be investigated. This was primarily based on its matching to the beam characteristics bunch length of the proton beam, which is in the range of few ns, and the beam current, which is in the range 0.1 - 10 nA. Furthermore, the demand for a high accuracy measurement of beam current and position, along with the easier construction due to radial symmetry and the absence of mechanically moving systems, played a leading role in the choice of the cavity resonator.

6.2 Dielectric-filled Reentrant Cavity Resonator (BCM)

We have investigated the principle of a dielectric-filled reentrant cavity resonator as a Beam Current Monitor (BCM) with the help of ANSYS HFSS. The evolution of the BCM designs follows from the excitation of the monopole mode (TM_{010}) resonance in a pillbox resonator. The cavity resonator has a TM_{010} mode resonance at 145.7 MHz. This is the second harmonic of the beam bunch repetition rate, which is 72.85 MHz. By performing the measurement at a harmonic of the RF frequency, interference with the much stronger signals from the cyclotron RF-cavities is suppressed. The second harmonic of the fundamental RF was chosen as this harmonic has the highest amplitude. In view of the relatively low beam current (0.1 – 1 nA) one of the important design criteria was to have the maximum beam-pickup coupling coefficient to excite the cavity. The choice of maximum beam-pickup coupling results in maximum signal power coupled out. As a consequence, the external quality factor of the cavity is lowered, which makes the obtained signal less sensitive to a small mismatch between the TM_{010} mode resonance frequency of the cavity and the drive signal of the beam. Macor was chosen as a dielectric for filling in the reentrant gap. The cavity BCM was designed with four inductive pickups; two small and two large. To aid in ease of resonance tuning, one of the unused large pickups is used as a resonance trombone. The pair of small inductive pickups are used for online verification of the resonance frequency. The cavity design has been optimized on the basis of detailed simulation studies of the effect of various parameters on the TM_{010} mode resonance frequency, quality factors and the beam-pickup coupling coefficients. The design with four pickups has the advantage to enable various studies on the cavity characteristics, at the expense of 50% lower signal power compared to a single pickup design.

The macor ring width and thickness, i.e., reentrant gap thickness, are the TM_{010} mode resonance tuning parameters. The pickup height, on the other hand, determines the loaded quality factor. A good agreement of the pickup signal, approximately 15 nV for a beam current of 1 nA from the cyclotron, was observed between the simulation and an analytical estimate, which established a solid base for the construction of the prototype.

With a BCM prototype, test-bench characterization of the prototype was performed as an S-parameter analysis with and without a beam analog, which is represented by a stretched wire. The S-parameter analysis performed in the absence of stretched wire confirmed the simulation results, except for the resonance frequency of the prototype, which was approximately 2% higher than the design frequency. This was due to a 5% difference in the dielectric constant of the macor ring. Using a new macor ring, the TM_{010} mode resonance frequency was matched to 145.7 MHz and the pickup signal corresponded to 15 nV for 1 nA beam current equivalent, in agreement with the simulations. The digitizer input signal level is expected at 0.031 $V_{peak\text{-}peak}$, when integrated over 1 second for 1 nA beam current and is expected to be 27 dB higher than the background noise.

The BCM prototype was installed in the PROSCAN beamline, at approximately sixteen meters from the degrader exit. In the PROSCAN beamlines, the bunch length is increasing with increasing distance to the energy degrader because of the significant energy spread in the beam introduced by the degrader. This reduces the second harmonic amplitude of the bunch and thereby the sensitivity of the measurement system.

The resonator response was measured with respect to an ionization chamber (IC) for different beam energies in the range 238 - 70 MeV. The measured resonator sensitivity was in good agreement (5% difference) with the simulated sensitivity. The lowest measurable beam current corresponds to 0.15 nA, with a 3σ resolution of 0.05 nA. These values are achieved with a signal integration over 1 second.

The signal sensitivity of the cavity resonator can be improved by approximately a factor of 1.5, either by leaving the unused pickup ports electrically open or with adapted matching circuits on the measurement port. This can lower the detection threshold to 0.1 nA with a resolution of 0.03 nA. Replacing the lossy-dielectric macor with a relatively loss-free dielectric, such as alumina, could enhance the signal level for 1 nA beam current by approximately 2.5 nV (17.5 nV with alumina) for the same design as the prototype (15 nV with macor).

6.3 Four-quadrant Dielectric-filled Reentrant Cavity Resonator (BPM)

A four-quadrant dielectric-filled reentrant cavity resonator has been designed to function as a beam position monitor. The characteristics of the dipole mode (TM_{110}) in a conventional pillbox cavity served as the basis for identifying the parameters that most affect the magnitude of the output signal as a function of beam position offset. These parameters were identified as the normalized shunt impedance, beam-coupling coefficient and pickup coupling coefficient. The choice of the dielectric ring in the reentrant gap is high-purity (99.5%) alumina, unlike macor in the BCM prototype. The reason is to have a higher quality factor of the TM modes since this will give a higher overall signal, which leads to better signal to noise and signal to background ratio. Contrary to the BCM, in the BPM, a high quality factor is needed to distinguish contributions from different TM oscillations.

Using ANSYS HFSS, a parametric investigation was made with the objective of a compact dipole cavity BPM design, which would deliver maximum signal output for a given beam current and position offset. These investigations were performed by varying the gap between the individual cavities, the gap between the grounded cylinder and the cavities, the dielectric width and thickness, and the pickup position. From these investigations, the optimal mechanical dimensions of the BPM prototype were obtained to achieve maximum beam-pickup coupling of the dipole mode at 145.7 MHz. For a sinewave at 145.7 MHz and an amplitude of 1 nA, and a position offset of 2 mm, we found a good agreement between the simulated (20.5 nV) and the analytical (25 nV) estimates of the pickup signal. This was considered a solid basis for the construction of the prototype.

The BPM prototype was characterized on a stand-alone test-bench with S-parameter measurements, both with and without a stretched wire, which simulates the proton beam. The results from the first S-parameter investigation resulted in a matched dipole resonance frequency of both the X plane and Y plane cavities.

We found that the position sensitivity was highly sensitive to spurious RF interference, impedance mismatch, and cavity asymmetries. In an HFSS simulation, the effects of cavity asymmetries were investigated by adding a cavity shift, dielectric shift and a cavity rotation. We found that these asymmetries also contributed to a shift of the TM_{110} mode resonance frequency. In an accordingly improved version of the BPM, the signal level was within 5% of the simulation results for the zero beam position and within 16% for a 15 mm position offset.

The BPM prototype was installed in the beamline at only six meters from the degrader exit. Due to this short distance, the bunch length increase due to energy spread was very small, so that the amplitude degradation of the second harmonic component due to the energy spread in the beam was reduced. The BPM measurement was carried out in two stages: a beam current sweep for given position offsets and a beam position sweeps for given beam currents.

The beam current sweeps for a given position offset, performed at 138 MeV and 200 MeV, confirmed the linear response of the BPM prototype as a function of beam current. The average of the normalized (with the beam current) cavity response enabled us to quantify the necessary correction for a measurement-offset. Using this measurement-offset correction, the position signal did not depend on beam current, but for beam intensities smaller than 2.5 nA, this was within a large confidence interval. This measurement-offset is caused by cyclotron RF interference and other sources of background. For beam intensities higher than 2.5 nA, the normalized cavity response is nearly constant.

The position sensitivity of the X1 and the X2 cavities are measured at a beam energy of 138 MeV, over a range of 10 mm with respect to the center position. For the X1 cavity, the linear response extends over the range -10.0 mm to +3.0 mm. The linear response of the X2 cavity extends over a larger range of - 10.0 mm to +10.0 mm due to its 30% higher position sensitivity as compared to the X1 cavity. The difference in position sensitivity between X2 and X1 cavity is attributed to cavity asymmetries introduced inadvertently during the reassembly. We also found a difference in the position sensitivity for two different beam currents: at 12.2 nA it is 12% higher than at 2.6 nA. This is explained by the influence of the fluctuations in the measurement-offset, whose magnitude was subtracted from the measured signal. However, in the beam position measurement, the measurement-offset is a vectorial combination of the contribution of the TM_{010} mode at the measurement frequency, the interference of the RF system and other sources of background. Therefore, when using a vector measurement of the measurement-offset, i.e., both its amplitude and phase, this difference in the position sensitivity might be reduced. For the beam position measurements, these fluctuations of the measurement-offset affect the measurement quality when the product of the beam current and beam position offset is ≤ 2.5 nA mm. A measurement procedure has been proposed that takes these vectorial compensations into account.

The resolution of the X2 cavity varied between 0.26 mm at 2.6 nA and 0.14 mm at 12.2 nA. The resolution of the X1 cavity was similar (within 10%) at both beam currents. The measured position resolution is within the 0.5 mm required for the PROSCAN beamlines.

An important observation was that the X2 cavity signal did not change by more than 2% for a beam position sweep in Y-axis in the range ± 10 mm (with respect to the center position). This is a clear indication of the non-excitation of the horizontal polarization of the dipole mode for beam position offsets in the vertical plane. This observation validated the dipole mode characterization of the BPM prototype.

A new improved BPM design was considered to improve the position sensitivity by a factor of 2.4 compared to the installed BPM prototype. An improvement in the signal at zero beam offset will help in this respect. This can be achieved by lowering the contribution of the TM_{010} mode at 145.7 MHz by 25% (4 nV reduction) and by increasing the signal amplitude containing position information by 44% (12 nV improvement) at a 5 mm offset. This improvement has been realized recently by an increase of the gap thickness to gap radius ratio, an increase of the azimuthal coverage of the cavities and an improvement of the loaded quality factor by alumina with lower losses. Experimental confirmation of these improvements has been planned to be performed soon.

In our cavity design, for a given position offset, the superposition of the TM_{010} and TM_{110} modes causes the signals from the two oppositely placed cavities to have different signal levels, which is not the case in a pillbox cavity. This is important as it allows determination of the sign of the displacement, for which we otherwise would need RF phase information from another cavity.

6.4 Pros and Cons of the Cavity Monitors

The application of cavity monitors for measurement of beam current and position at PROSCAN has its advantages and disadvantages, as compared to the existing beam diagnostics. These are summarized below:

6.4.1 Advantages of Cavity monitors with respect to Interceptive monitors

- Mitigation of scattering and secondary halo. The beam quality and emittance are thus better preserved until delivery to patients.
- A non-interceptive monitor can remain in the beamline continuously, unlike in the situation of ICs, which have to be taken out of the beamline during patient treatment.
- Unlike in ICs, the cavity monitors are not subject to measurement saturation in case of small beam sizes or at higher beam currents (without considering saturation possibilities in amplifiers and digitizers).
- No extra measures are needed for the protection of the cavity resonators, unlike for secondary emission monitors (SEMs) where the detector foils have to be protected against overheating.
- Activation of the cavity resonator is reduced compared to interceptive monitors.

6.4.2 Disadvantages with respect to Interceptive monitors

- Resonating cavity monitors require other monitors for calibration procedures. For low beam currents, in the range 0.1-10 nA, the calibration can be performed with interceptive monitors only. Therefore the demand for an interceptive monitor at PROSCAN always will remain.
- The response of resonating cavity monitors is deteriorating at a shorter integration time. Thus, their application is limited to interlock triggers as in patient safety systems.
- Resonating cavity monitors developed for PROSCAN have their detection limit down to 0.15 nA. Interceptive monitors have a lower detection threshold and faster integration time than the resonating cavity monitors.
- Reduced sensitivity of resonating cavity monitors with distance from the degrader exit.
- Any relocation of a resonating cavity monitor necessitates a new calibration for evaluation of measurement sensitivity (beam current and position), unlike in interceptive monitors.
- The presence of other TM oscillations close to the frequency of interest affects the measurement sensitivity (both beam current and position) of resonating cavity monitors.

Considering the advantages and disadvantages of cavity resonators with respect to existing interceptive monitors, we conclude that our resonating cavity monitors can be used to trigger interlocks as a machine safety measure at PROSCAN within the existing treatment and operation procedures.

6.5 Future development and limitations

The trend in proton therapy is shifting towards compact, single-room treatment facilities since multi-room facilities have high investment costs. With a single-room facility, which is mostly based on synchrocyclotrons, the influence of energy spread from the degrader on the bunch length and thereby the second harmonic amplitude will be limited greatly, as the distance from a degrader to the treatment isocenter is much shorter, generally in the range of 20 m. This would ease the use of cavity resonators for beam current and position measurement as their measurement sensitivity is not as drastically affected as in the long beamlines associated with multi-room facilities. Moreover, with a shorter beamline, the necessity to calibrate in case of the cavity’s relocation is reduced. However, the initial calibration will still require the use of an interceptive monitor.

Another trend in proton therapy that is currently investigated is FLASH irradiation [1]–[3]. The FLASH irradiation studies performed at PROSCAN require pulsed beam currents in the range of 80-500 nA with a pulse length shorter than 100 ms. The requirement of high proton beam currents is a perfect situation for cavity resonators. Even though the irradiation time is limited to 100 ms, beam current for FLASH irradiation will lead to saturation effects (yielding sensitivity decrease) in ionization chambers but will enhance the signal level from the cavity monitors linearly such that the power output from the cavity is improved by approximately 40 dB compared to 1 nA beam current scenario. This allows a reduction of the signal integration time to only approximately a few hundred microseconds. In such a scenario, the use of interceptive monitors for beam parameter monitoring can be minimized except for their use for the initial calibration of the cavity resonators.

With the potential to combine both growing trends in proton therapy, i.e., a single-room treatment Proton FLASH facility, we see a growing potential for cavity resonators as a tool for beam monitoring owing to the fact that their disadvantages can be mitigated to a greater extent.

6.6 References

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