

University of Groningen

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

Srinivasan, Sudharsan

DOI:

[10.33612/diss.149817352](https://doi.org/10.33612/diss.149817352)

**IMPORTANT NOTE:** You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

*Document Version*

Publisher's PDF, also known as Version of record

*Publication date:*

2021

[Link to publication in University of Groningen/UMCG research database](#)

*Citation for published version (APA):*

Srinivasan, S. (2021). *Non-Interceptive Beam Current and Position Monitors for a Cyclotron Based Proton Therapy Facility*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen. <https://doi.org/10.33612/diss.149817352>

### Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

### Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

*Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.*

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



university of  
 groningen



The research presented in this thesis has received funding from the European Union's Horizon 2020 research and innovation programme, Optimization of Medical Accelerators (OMA), under the Marie Skłodowska-Curie grant agreement No 675265.

© 2021 Sudharsan Srinivasan

Printed by Copy 76

Cover designed by Laxsha Srinivasan



university of  
 groningen

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

**PhD thesis**

to obtain the degree of PhD at the  
University of Groningen  
on the authority of the  
Rector Magnificus Prof. C. Wijmenga  
and in accordance with  
the decision by the College of Deans.

This thesis will be defended in public on  
Wednesday 13 January 2021 at 11.00 hours

by

**Sudharsan Srinivasan**

born on 25 January 1990  
in Kumbakonam, India

## **Supervisors**

Prof. S. Brandenburg  
Prof. J.M. Schippers

## **Co-supervisor**

Dr. P.A. Duperrex

## **Assessment Committee**

Prof. A.M. van den Berg  
Prof. O. Jäkel  
Prof. C. Welsch

# Abbreviations

<b>ADC</b>	Analog-to-Digital Converter
<b>ATF</b>	Accelerator Test Facility
<b>AWA</b>	Argonne Wakefield Accelerator
<b>BALUN</b>	Balanced to Unbalanced
<b>BCM</b>	Beam Current Monitor
<b>BCT</b>	Beam Current Transformer
<b>BP</b>	Bandpass
<b>BPM</b>	Beam Position Monitor
<b>CTF3 DBL</b>	CLIC Test Facility 3 Drive Beam Linac
<b>CW</b>	Continuous Wave
<b>DDC</b>	Digital Down Converter
<b>DUT</b>	Device Under Test
<b>ESS</b>	Energy Selection System
<b>FC</b>	Faraday Cup
<b>FPGA</b>	Field Programmable Gate Array
<b>HFSS</b>	High Frequency Structure Simulator
<b>HOM</b>	Higher Order Mode
<b>IC</b>	Ionization Chamber
<b>IPHI</b>	Injecteur de Protons à Haute Intensité
<b>NSLS – II</b>	National Synchrotron Light Source –II
<b>PIF</b>	Proton Irradiation Facility
<b>PEEK</b>	Polyether Ether Ketone
<b>PSI</b>	Paul Scherrer Institut
<b>Q</b>	Quality Factor
<b>S</b>	Scattering parameters
<b>SEM</b>	Secondary Emission Monitor

<b>SNR</b>	Signal-to-Noise Ratio
<b>TE</b>	Transverse Electric
<b>TEM</b>	Transverse Electromagnetic
<b>TM</b>	Transverse Magnetic
<b>TSOM</b>	Through, Short, Open, Match
<b>WCM</b>	Wall Current Monitor

# Abstract

In PSI's dedicated proton therapy facility PROSCAN a pulsed 250 MeV proton beam is delivered by a superconducting cyclotron. During the proton-irradiation treatments, there is a need to accurately measure beam current, in the range of 0.1-10 nA, and beam position (required accuracy 0.5 mm). The beam current is directly associated with the dose-rate in the treatment and the beam position with the quality of the dose distribution in the patient. However, the presently used measurements compromise the beam quality. Nevertheless, it is a necessity to perform these measurements online and with minimal beam disturbance. This thesis reports on the development of two types of cavity resonators to perform non-interceptive measurements of these beam parameters, within the required accuracy.

For beam current measurements, a single cavity resonator has been built. For the beam position measurements, a cavity resonator consisting of four separate segments has been built. Both cavity resonators have been tuned to the second harmonic of the beam pulse rate, i.e., 145.7 MHz. In test bench experiments and with proton beams, a good agreement between the expected and measured sensitivity of these resonators has been found. The cavity used to measure beam current can measure currents down to 0.15 nA with a resolution of 0.05 nA. The cavity for measuring beam position delivers position information with the required accuracy and resolution demands of 0.5 mm. The design, tests and performance in the beam as well as special applications, future improvements and limitations are discussed.





# Table of Contents

<b>Chapter 1 : Introduction .....</b>	<b>1</b>
1.1 Radiation therapy .....	1
1.2 PROSCAN: COMET, its beamlines and diagnostics .....	2
1.2.1 COMET cyclotron.....	3
1.2.2 Degradar.....	3
1.3 PROSCAN beam diagnostics.....	4
1.3.1 Drawbacks of the existing diagnostics.....	4
1.4 Beam diagnostic measurement specifications for PROSCAN.....	5
1.5 Parameters of Interest: Beam Current and Beam Position.....	6
1.6 Interceptive Beam Diagnostics .....	7
1.6.1 Faraday cups (FCs) .....	7
1.6.2 Ionization chambers (ICs).....	8
1.6.3 Secondary Emission Monitors (SEMs).....	8
1.7 Non-interceptive beam diagnostics.....	9
1.7.1 Beam Current Transformers (BCTs).....	9
1.7.2 Capacitive monitors .....	9
1.7.3 Wall Current Monitors (WCMs).....	10
1.7.4 Cavity resonators.....	10
1.8 Aim of the thesis .....	11
1.9 Overview of the Thesis .....	13
1.10 Appendix.....	15
1.11 References.....	16
<b>Chapter 2 : Design and Simulation of a Dielectric-filled Reentrant Cavity Resonator as Proton Beam Current Monitor .....</b>	<b>21</b>
2.1 Introduction.....	21
2.1.1 Maxwell equations in a simple pillbox RF Cavity.....	22

2.1.2	Approximation of the coaxial cavity from an LC model .....	24
2.1.3	Cavity Parameters: Q (Quality Factor) and coupling coefficient.....	27
2.1.4	Beam cavity interaction .....	28
2.2	Second harmonic matching.....	30
2.3	Simulation objective .....	31
2.4	ANSYS HFSS.....	32
2.4.1	Design overview .....	34
2.4.2	Eigenmode Solution Setup.....	36
2.4.3	Driven modal Solution Setup.....	39
2.5	Analytical vs Simulation of the pickup amplitude.....	48
2.6	Conclusion .....	49
2.7	Cut-plane of the prototype resonator .....	50
2.8	Appendix.....	51
2.9	References.....	52

### **Chapter 3 : Prototype Tests of the Proton Beam Current Monitor (BCM)55**

3.1	Introduction.....	55
3.2	Purpose of a test-bench .....	55
3.3	Stand-alone test-bench and its components .....	56
3.3.1	Beam Current Monitor and its assembly components .....	57
3.3.2	Beam analog.....	58
3.4	S-parameter measurements .....	58
3.4.1	Mutual pickup S-transmission ( $S_{ji}$ ) results.....	59
3.4.2	Resonance frequency optimization .....	62
3.4.3	Beam-Pickup S-transmission parameter .....	63
3.5	Beamline characterization.....	65
3.5.1	BCM location in the PROSCAN layout and the effect of bunch length.....	66
3.5.2	Measurement chain .....	68

3.6 Measurement results .....	70
3.6.1 No-beam response with and without the resonator .....	70
3.6.2 In-beam resonator response .....	70
3.7 Discussion .....	75
3.8 Conclusion .....	77
3.9 Appendix.....	78
3.10 References.....	79
<b>Chapter 4 : Design of a Four-quadrant Dielectric-filled Reentrant Cavity Resonator as a Proton Beam Position Monitor (BPM) Using HFSS Simulation.....</b>	<b>81</b>
4.1 Introduction.....	81
4.1.1 Dipole mode (TM <sub>110</sub> ) cavity characterization .....	82
4.2 Design Considerations .....	86
4.2.1 TM <sub>110</sub> mode polarization.....	86
4.2.2 Choice of Cavity type: Pillbox vs Dielectric-filled Reentrant .....	87
4.2.3 Choice of Coupling: Magnetic.....	88
4.2.4 Choice of materials and dimension limitations.....	88
4.3 ANSYS HFSS simulations.....	89
4.3.1 Eigenmode Solution Setup.....	90
4.3.2 Driven modal Solution Setup.....	93
4.4 Final BPM model and simulation results for position offsets.....	103
4.4.1 S-transmission for position offsets.....	103
4.4.2 Crosstalk (XX and XY).....	108
4.4.3 Cavity asymmetries.....	112
4.5 Analytical evaluation .....	115
4.6 Conclusion .....	116
4.7 Appendix.....	118
4.8 References.....	119

<b>Chapter 5 : Prototype Tests of the Four-quadrant Dielectric-filled Reentrant Cavity Resonator as a Proton Beam Position Monitor (BPM)</b>	<b>121</b>
5.1 Introduction.....	121
5.2 Purpose of a test-bench .....	121
5.3 S-parameter measurements .....	122
5.3.1 $S_{\text{beam-pickup}}$ measurements .....	123
5.3.2 Conclusion on sensitivities.....	124
5.4 Beamline measurements .....	128
5.4.1 Beam current response .....	130
5.4.2 Beam position response .....	134
5.5 New version of the BPM Design: Overview .....	141
5.6 Summary .....	144
5.7 References.....	147
<b>Chapter 6 : Summary and Outlook.....</b>	<b>149</b>
6.1 Review: thesis objective .....	149
6.2 Dielectric-filled Reentrant Cavity Resonator (BCM) .....	149
6.3 Four-quadrant Dielectric-filled Reentrant Cavity Resonator (BPM).....	151
6.4 Pros and Cons of the Cavity Monitors .....	153
6.4.1 Advantages of Cavity monitors with respect to Interceptive monitors .....	154
6.4.2 Disadvantages with respect to Interceptive monitors.....	154
6.5 Future development and limitations.....	155
6.6 References.....	156
<b>Nederlandse samenvatting .....</b>	<b>157</b>
Trilholte voor meting bundelintensiteit.....	157
Vier-kwadrant trilholte voor meting bundelpositie.....	160
Voor- en nadelen van trilholtes voor meting van bundeleigenschappen .....	166
<b>Acknowledgments .....</b>	<b>167</b>
<b>Sudharsan Srinivasan (CV) .....</b>	<b>169</b>



