

Development of a Laser-based Emittance Monitor for Negative Hydrogen Beams

Entwicklung eines Laser-basierten Messgeräts
zur Ermittlung der Emittanz von Negativen
Wasserstoffionenstrahlen

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Abstract

High energy particle accelerators are designed to collide charged particle beams and thus study the collision products. Maximising the collision rate, to generate sufficient statistics for precise measurements of rare processes, is one of the key parameters for optimising the overall collider performance.

The CERN Large Hadron Collider (LHC) Injectors Upgrade (LIU) includes the construction of LINAC4, a completely new machine working as a first linear acceleration stage for the LHC beam. By accelerating a negative hydrogen beam (H^-) instead of protons, it aims to double the beam brightness via a more efficient transfer to the first circular accelerator and subsequently boost the LHC collision rate. To achieve this, a precise knowledge of the transverse beam characteristics in terms of beam emittance is essential.

This thesis work covers the development of a laser-based monitor meant to measure non-destructively the LINAC4 beam transverse profile and emittance. This included the implementation of different prototypes that were successfully tested at various beam energies during the LINAC4 commissioning and the design of the final system to be installed at the LINAC4 top energy.

The laser emittance meter is based on the photo-detachment effect which describes the liberation of an electron from a negative hydrogen ion. By scanning a focused laser-beam through the H^- beam, the profile can be reconstructed by counting the amount of the detached electrons. The transverse emittance can be obtained by separating the H^0 from the H^- beam by a dipole magnet and recording the H^0 profiles downstream the dipole for each laser position.

The thesis work introduces the basic principles of transverse beam dynamics and the techniques typically used to determine the transverse beam characteristics. Hereafter a bibliographic research is presented about the state of the art in the field of beam diagnostics based on photo-detachment.

Then, an extensive simulation campaign of the photo-detachment process led to the conclusion that the laser-system can be based on a low-power laser-source and a fibre-optic transfer of the laser beam to the interaction point with the H^- beam. To distinguish the H^0 created by the laser interaction from background radiation, a fast, sensitive and radiation-hard diamond strip-detector

was implemented. First tests of a prototype were conducted at a 3 MeV and 12 MeV H^- beam and the results were compared with conventional techniques, which resulted to agree within $\pm 3\%$ in terms of emittance.

In the following LINAC4 beam commissioning periods at 50, 80 and 107 MeV a second prototype of the instrument based on monitoring the detached electrons has been validated. The setup, consisting of a laser system with 73 m long fibre-optic transfer line, electron deflector magnet and single-crystal diamond detector, has been fully characterised and the obtained profiles were compared with conventional techniques, where an agreement within $\pm 2\%$ has been found.

All these prototype tests were essential for the design of permanent installations at the LINAC4 top energy of 160 MeV in the transfer-line towards the injection into the successive machine (PS-Booster). The design combines electron and H^0 detection and provides a simultaneous emittance and profile measurement in the horizontal and vertical planes, with an expected resolution of $< 75 \mu\text{m}$ and $< 100 \mu\text{rad}$. The instruments shall be routinely operated for automated on-line monitoring of the transverse beam parameters to optimise the PS-Booster injection and subsequently avoid losses and the consequent activation of the environment. Due to the non-destructive measurement method, the instrument can gather an extensive amount of beam characteristics data without leading to downtimes of the machine.

Zusammenfassung

In Hochenergie-Teilchenbeschleunigern wie dem Large Hadron Collider (LHC) prallen geladene Teilchenstrahlen aufeinander, wodurch eine Analyse der Kollisionsprodukte ermöglicht wird. Um sehr seltene Prozesse mit hinlänglicher statistischer Signifikanz zu beobachten ist die Kollisionsrate des Teilchenbeschleunigers entscheidend.

Im Rahmen von CERNs LHC Injectors Upgrade (LIU) soll der neue Linearbeschleuniger LINAC4 negative Wasserstoff Ionen (H^-) auf 160 MeV beschleunigen. Durch eine effiziente Einspeisung in den nachfolgenden Kreisbeschleuniger soll die Leuchtdichte des Teilchenstrahls verdoppelt werden und somit die Kollisionsrate des LHCs gesteigert werden. Um dies zu erreichen ist die präzise Kenntnis der transversalen Strahlcharakteristik in Sinne der Strahl-Emittanz essenziell.

Die vorliegende Arbeit behandelt die Entwicklung eines laser-basierten Messgeräts zur zerstörungsfreien Erfassung des transversalen Strahlprofils und der transversalen Emittanz. Dafür wurden verschiedene Prototypen bei unterschiedlichen Teilchenstrahl-Energien während der Inbetriebnahme getestet. Anschließend wurde ein finales Messgerät entwickelt welches langfristig im Hochenergiebereich des LINAC4 integriert werden wird.

Die laser-basierte Emittanzmessung beruht auf dem Photo-Detachment Effekt, der die Ablösung eines Elektrons von einem negativen Wasserstoff-Ion beschreibt. Wird ein fokussierter Laserstrahl durch den H^- Strahl gesannt, werden freie Elektronen erzeugt, mithilfe derer das H^- Strahlprofil rekonstruiert werden kann. Die generierten H^0 Teilchen können durch einen Dipol-Magneten vom H^- Hauptstrahl separiert werden. Mittels Messung der H^0 Winkelverteilung kann somit die transversale Emittanz bestimmt werden.

In der Dissertation werden zu Beginn die Grundlagen der transversalen Strahldynamik behandelt und klassische Techniken zur Bestimmung der transversalen Strahlparameter erläutert. Der Stand der Technik für laser-basierte Verfahren zur Strahlprofil- und Emittanz-Messung wird mittels einer Literaturrecherche zusammengefasst.

Daraufhin werden umfassende Simulationen des Photo-Detachment Prozesses beschrieben, die zum Ergebnis führen, dass eine Laserquelle mit vergleichsweise niedriger Puls-Spitzenleistung im Kilowattbereich und ein faseroptischer Strahltransport zum Interaktionspunkt die Systemanforderungen erfüllen. Um die vom Laserstrahl erzeugten H^0 von Hintergrundstrahlung zu unterscheiden, wurde ein schneller, empfindlicher und strahlungsfester Diamant-Detektor implementiert. Erste Prototypentests wurden auf einer H^- Strahlenergie von 3 MeV und 12 MeV durchgeführt und mit konventionellen Messmethoden verglichen. Die Emittanzmessungen stimmen mit einer Genauigkeit von $\pm 3\%$ überein.

In der darauffolgenden LINAC4 Inbetriebnahmephase mit Strahlenergien von 50, 80 und 107 MeV wurde ein zweiter Prototyp getestet, welcher durch Detektion der freigesetzten Elektronen das Strahlprofil rekonstruierte. Dieser Aufbau bestand aus einem Laser-System, einem 73 m langen faseroptischen Transfer des Laserstrahls, einem Elektron-Ablenkmagneten und einem Einkristall-Diamantdetektor. In der Testkampagne wurden diese Subsysteme eingehend charakterisiert und die erhaltenen Strahlprofile mit konventionellen Messmethoden verglichen. Dabei wurde eine Übereinstimmung von $\pm 2\%$ festgestellt.

Die beschriebenen Prototypentests waren essenziell, um Messsysteme für permanente Installationen im Hochenergie-Bereich (160 MeV) des LINAC4 zu entwickeln. Profil- und Emittanz-Messungen in horizontaler und vertikaler Ebene mit einer Auflösung von $< 75 \mu\text{m}$ und $< 100 \mu\text{rad}$ werden durch kombinierte Detektion von Elektronen und H^0 ermöglicht. Die Messgeräte sollen routinemäßig für automatisierte Messungen der transversalen Strahlparameter eingesetzt werden, um die Einspeisung in den nachfolgenden Beschleuniger PS-Booster zu optimieren und somit Verluste und damit einhergehende Radioaktivität zu vermeiden. Da es sich um eine zerstörungsfreie Methode handelt, können die Geräte permanent Strahlcharakteristik-Daten aufnehmen, ohne Ausfallzeiten des Beschleunigers zu verursachen.

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Contents

Abstract	III
Zusammenfassung	V
Acknowledgements	VII
List of Symbols and Abbreviations	XIII
1 Introduction	1
1.1 LHC Injector Upgrade and High-Luminosity LHC	2
1.2 LINAC4	4
1.2.1 Charge Exchange Injection	5
1.2.2 Emittance Measurements at LINAC4 Top Energy . . .	7
1.3 Thesis Contents	8
2 Particle Beam Parameters and Measurement Techniques	11
2.1 Principles of Beam Dynamics	11
2.1.1 Acceleration Principle	11
2.1.2 Transverse Beam Dynamics	12
2.1.3 Transverse Emittance	16
2.2 Conventional Profile and Emittance Measurement Techniques	17
2.2.1 3-Profile and Quadrupole-Scan Method	18
2.2.2 Pepper-Pot	20
2.2.3 Slit/Grid	21
2.2.4 Wire-Scanner	22
2.2.5 Summary	23

3	Concept of the Instrument	25
3.1	Photo-Detachment of H^- Ions	25
3.2	Concepts for Different Instrument Types	27
3.2.1	Laser-based Transverse Profile Measurement	27
3.2.2	Laser-based Transverse Emittance Measurement	29
3.3	State of the Art of Laser Based H^- Diagnostics	30
4	Design Considerations	33
4.1	LINAC4 Beam Parameters at 160 MeV	33
4.2	Photo-Detachment Model	34
4.2.1	Analytical Description of Yield	35
4.2.2	Single Particle Behaviour	36
4.2.3	Relativistic Doppler Effect	37
4.3	H^- Background Evaluation	38
4.3.1	Residual Gas Stripping	38
4.3.2	Intra-Beam Stripping	39
4.3.3	Black Body Radiation	40
4.3.4	Magnetic Field Stripping	40
4.3.5	Summary of H^0 Background Sources at LINAC4	41
4.3.6	Model for H^0 Background at Detector 1	42
4.4	Laser System	44
4.4.1	Transverse Profile and Beam Quality	45
4.4.2	Fibre-based Laser Transport	46
4.4.3	Laser Pulse Timing	53
4.4.4	Peak Power	55
4.4.5	Summary of Laser Requirements	56
4.5	H^0 Detector	56
4.5.1	Requirements	57
4.5.2	Review of Potential Detector Systems	58
4.5.3	Diamond Detector	59
5	Emittance Measurements at 3 MeV and 12 MeV H^- Beam	69
5.1	Experimental Setup	69
5.1.1	Diagnostic Test-bench	70
5.1.2	Laser System	71
5.1.3	Detector System	75

5.1.4	DAQ and Controls System	79
5.2	System Characterisation and Commissioning	80
5.2.1	Laser System	80
5.2.2	Detector System	85
5.3	3 MeV H ⁻ Beam Tests	88
5.3.1	Simulation of Laser Interaction and H ⁰ Background	88
5.3.2	Diamond Detector Signal Examination	90
5.3.3	Data Analysis Method	93
5.3.4	Results	93
5.4	12 MeV H ⁻ Beam Tests	98
5.4.1	Instrument Setup Changes	98
5.4.2	Instrument Re-characterisation	100
5.4.3	H ⁻ Beam Parameters	102
5.4.4	Simulation of Diamond Detector Signal	102
5.4.5	System Characterisation on H ⁻ Beam	102
5.4.6	Data Analysis and Results	106
5.5	Summary	110
6	Profile Measurements at 50, 80 and 107 MeV H⁻ Beam	113
6.1	Experimental Setup	113
6.1.1	Diagnostic Test-bench with Laser Profile Monitor	113
6.1.2	Laser System	114
6.1.3	Electron Detection	119
6.2	System Characterisation	125
6.2.1	Laser Characteristics at IP	125
6.2.2	Response of sCVD Diamond Detector	127
6.3	H ⁻ Beam Measurements	129
6.3.1	H ⁻ Beam Parameters	129
6.3.2	System Characterisation on H ⁻ Beam	130
6.3.3	H ⁻ Beam Profile Measurements	136
6.3.4	Comparison of Results with Conventional Techniques	137
6.4	Summary	140
7	Instrument Design for 160 MeV H⁻ Beam	141
7.1	LINAC4 160 MeV Region	141
7.1.1	160 MeV H ⁻ Beam Parameters	142
7.2	Photo-Detachment Simulation	143

7.2.1	Interaction Yield	143
7.2.2	H^0 Beamlets	144
7.2.3	H^0 Background	146
7.3	Instrument Design	146
7.3.1	Laser System	146
7.3.2	Electron Detection	149
7.3.3	H^0 Detection	154
7.3.4	DAQ and Control System	163
7.4	Status and Next Steps	168
8	Summary and Outlook	171
8.1	Summary	171
8.2	Outlook	172
A	Beam Dynamics	175
B	Schematics	179
C	Supplementary Plots	185
	Bibliography	191
	List of Figures	198
	List of Tables	204