Project Report

"LIGHT – Laser Ion Generation, Handling and Transport"

Collaboration partners

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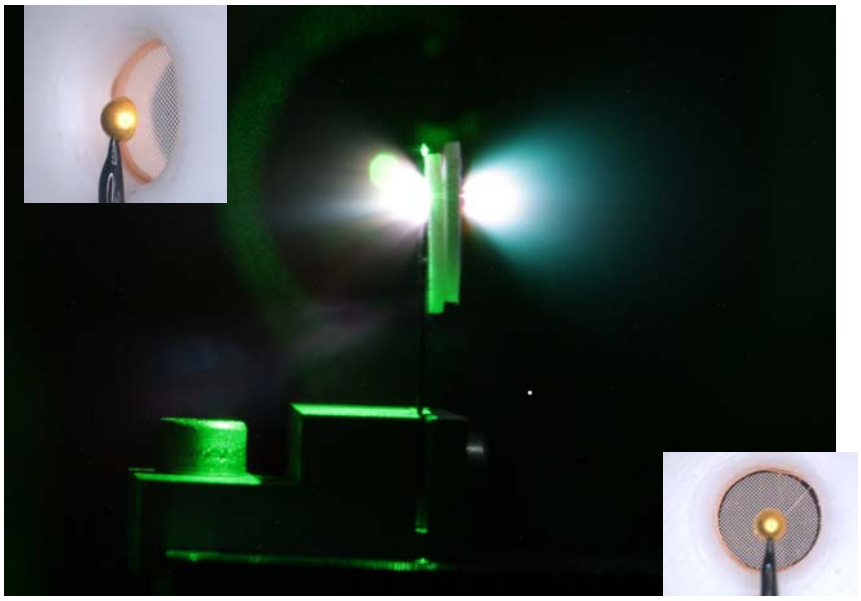
Executive Summary

An experimental project is proposed, which makes use of protons (ions) accelerated by means of the PHELIX laser at GSI and provides transport, focusing and bunch rotation of the laser generated particle bunches by conventional ion optics and RF technology in a "test stand" located at the Z6 experimental area of GSI. The experiment planned for 2010-2012 is the first systematic exploration of the interface between laser acceleration (based on "target normal sheath acceleration") and conventional accelerator technology. It combines in a unique and highly efficient way the capabilities of PHELIX as world-class high power (100 TW) laser with the accelerator know-how available at GSI; the target and plasma physics expertise at TU Darmstadt; the expertise in lasers of the Helmholtz Institute Jena; the high field magnet technology at the FZ Dresden-Rossendorf; the accelerator expertise of the IAP Frankfurt.

Proton acceleration by lasers currently reaches energies in the range of 30-60 MeV. It opens new perspectives for future application as novel medium energy accelerators: possibly in the areas of medical treatment, material studies or energy research. The scientific goal of the proposed experiment is to explore several critical interfaces, which are the basis of any future application: de-neutralization of the neutralized particle bunch in a collimation magnetic field; collimation of the broad energy (10-30 MeV) and divergence angle (up to 25 degrees) production spectrum of protons/ions by a pulsed solenoid as first collimator; transport through a drift or focusing channel; RF bunch rotation to complete the de-bunching of the originally sub-ps bunches to ns; diagnostics of the 6D phase space by means of a sub-ns streak camera and pepper-pot emittance devices.

The resources needed over the three years duration (phases 1-3) are shared by the partner institutions. Besides staff from existing research activities, a total of 6 PHD students are planned for the experimental and theoretical research. The investment and consumables cost estimates are 175 k€ for the first year, 115 k€ for the second and 40 k€ for the third year. The required optomechanical, laser compressor and beam line components to Z6 have been funded with 320 k€ from previous projects.

Table of contents



Proton acceleration experiment at the GSI-PHELIX laser. The laser (from left) irradiates a hemispherical gold target of 600 µm diameter and 10 µm wall thickness. Behind the target two small meshes in white mounts are placed in the beam to determine the emittance and divergence angle.

1. Introduction

The development of ultrahigh-power laser systems in the last two decades has lead to increasing attention and enormous scientific activities in the field of laser-plasma interactions. In the focus of such laser beams, intensities up to 10^{22} W/cm^2 became available for experiments, and thus an entirely new area of research, the regime of relativistic plasma physics became accessible. Acceleration of protons and light ion species to several 10's of MeV by high-intensity laser beams has been very successful in recent years. The quality of these beams is quite different from beams produced in conventional accelerator structures: they have extremely small longitudinal and transverse production emittances, although their production energy spread and angular divergence are quite large (50-100%, respectively hundreds of mrad). Because of these challenging beam characteristics, discussions have been started about possible applications in:

- energy research ("Fast Ignitor" in the inertial fusion energy context),
- injection of high peak power ion beams for basic research facilities,
- medical treatment (proton and carbon therapy, transmutation of short lived radio-isotopes for positron emission tomography (PET) in hospitals) and
- the modification of material parameters (starting from applications in materials science up to warm dense matter research and laboratory astrophysics).

To prosper in these exciting applications, the fusion of laser-ion-acceleration and conventional ion accelerator technology is of main importance. The establishment of this connection is the main goal of this project. For this reason the decision was made to start a collaboration including GSI - Helmholtzzentrum für Schwerionenforschung

GmbH (GSI), Technische Universität Darmstadt (TUD), the newly founded Helmholtz-Institute Jena (HIJ), the Forschungszentrum Dresden-Rossendorf (FZD) and the Institute for applied Sciences at the University of Frankfurt (UF). The experimental part of the project is centered at GSI, which is a unique facility, combining a heavy ion accelerator with a laser system of the Petawatt-class, PHELIX (**P**etawatt **H**igh **E**nergy **L**aser for **I**on **Ex**periments). These are the ideal conditions for such a project. The collaboration gathers top level expertise in the required fields, ranging from Ultra-Intense Laser Sciences to High Magnetic Field experience to Target-, relativistic Laser Plasma- and Accelerator physics. A careful study of the transfer efficiency of these beams into conventional transport and focusing structures is crucial and timely, which can be carried out within the next three years given the unique prerequisites present among the partners. The foremost goal of the proposed effort is to find out the properties of the hereby generated proton/ion beams with the prospect of later applications and to examine the possibilities of collimation, transport, de-bunching and possibly post-acceleration in conventional accelerator structures both theoretically and experimentally.

GSI is predestined for such a project, since on one hand, a high power, high energy laser is available with the PHELIX system linked to an existing ion accelerator. On the other hand the collaboration with the Darmstadt University plasma physics research team, the Institute of Applied Physics of Frankfurt University accelerator department, the recently founded Helmholtz Institute Jena and the FZ Dresden-Rossendorf offer numerous possibilities and competences in the relevant fields as will be shown in the proposal sections. The following section will present the main objectives of the project followed by a short description of the current status, the proposed layout of the experimental area and the functional description of the individual components. Those will be technically specified in the following section which relies on preparative work of the collaboration partners prior to this proposal. The experimental program will be highlighted in the section followed by a resource plan, timeline and milestones. For a more detailed description of the underlying physics, experiments and technical details of some of the components please refer to the appendix of this document.

2. Objectives

The new collaboration gathers top level expertise in the required fields, ranging from Ultra-Intense Laser Sciences, High Magnetic Field experience, Target Fabrication to Accelerator physics. The main goal for the new collaboration is to bring together the experts in the above mentioned field in order to:

- investigate the physics of ion beam generation by ultra-intense lasers with special respect to the generation of a laser-accelerated proton or possibly also light ion beam by irradiation of a target with the PHELIX laser with a resulting average particle energy E_0 of about 10 MeV.
- explore the applications, especially in combination with secondary laser and ion beams in high density plasma research
- to collimate the beam by a pulsed solenoid magnet and transport it to a bunch rotation cavity
- to analyze the 6D phase space distribution and transmission, in particular correlation between energy distribution and transverse divergence

- to optimize laser and target configurations as well as target solenoid stand-off distance and B-field for optimum transmission and phase space density and reproducibility of the beam parameters and
- to study the interaction with intense B-fields, especially in the context of early de-neutralization and space charge effects

3. Status and preparative work

3.1) Infrastructure

The preparation of the infrastructure in and around the Z6 area at GSI was already started in 2006 with the installation of the vacuum tank for the optical compressor. Due to spatial constraints, the necessary construction of a cleanroom environment around the PHELIX mirror towers would have prevented its later installation. With the setup of the PHELIX long pulse transport and 10° beamlines, the PHELIX laser beam became available in 2008 and has already been used for multiple combined ion/laser experiments. The addition of the on-site possibility to compress sub-aperture laser beams up to 100 TW peak power makes this system suitable for acceleration experiments in the same target area, including the existing target chamber. The target area is already fully equipped to handle the UNILAC ion beam, including vacuum beamlines, quadrupoles, RF sources, as well as basic radiation shielding. Until the beginning of the acceleration experiments, the area will be qualified for the expected ion energies in terms of radiation protection

3.2) Status of experiments

Acceleration experiments

The collaboration partners have a long lasting expertise in laser particle acceleration, and indeed have been participating in the very first experiments in this domain. For many years experiments have been conducted at various laser systems including the PHELIX laser and the JETI laser system in Jena. At GSI, the experimental program started in autumn 2008 with a campaign at PHELIX that was the first laser-ion-acceleration experiment at PHELIX at all. It was focused on the transport and collimation of the proton beams with the help of strong magnetic fields. Therefore, a pulsed high field solenoid was developed with a maximum magnetic field of 8.6 Tesla to parallelize the beam, since the protons are accelerated with full opening angles of more than 45°. The solenoid was pulsed by the PHELIX capacitor banks at 8 kV and 19 kA. Proton beams with up to 10^{12} particles and energies around 2.3 MeV to 5 MeV could be collimated, transported and detected along a distance of more than 300 mm [*3.1*]. In contrast to any prior experiment, in this experiment a transport efficiency of nearly 100% could be demonstrated for the given energy of 2.3 MeV, which is orders of magnitude higher than earlier attempts.

This experiment was the first proof of principle that a solenoid field is a practical device to catch the laser-accelerated proton beams after they were produced by the laser-plasma interaction.

A continuation experiment at PHELIX was started in November 2009 where a new solenoid developed by the Forschungszentrum Dresden was used. Within this experimental campaign, which continued in 2010, the transport, focusing and energy selection of laser-accelerated protons guided by the pulsed high-field solenoids was studied in detail. The protons were accelerated by the interaction of the CPA short pulse of the PHELIX with a thin metal foil. The solenoid was placed in a distance of

95 mm to the target to collimate the strong divergent beam and to parallelize the proton trajectories. By varying the field strengths of the solenoid, the desired proton energy could be selected, e. g. the protons were focused at an energy of 6.5 MeV and collimated at 13 MeV. These observations were verified by numerical simulations.
One of the main goals of the experiment was to investigate the ion transport and interaction with the co-moving electrons. Furthermore the influence of Eddie currents on the targets and the variation of target to magnet distance with special respect on chromatic and spherical aberrations were tested. The results have show that inside the solenoid strong space charge effects occur that influence the propagation of the ions.
In future experiments a new solenoid design will be used where the coil and the windings are in ambient air to provide a safer and more reliable operation at the high pulse currents and voltages see figure 6.4. The final aim will be to control the extraction and transport of a quasi-monoenergetic high flux proton beam.
Besides the work of the laser- and plasma group of Technical University of Darmstadt [3.*1, 3.2*] the transport of laser- accelerated protons was published by three different groups [*3.3-3.5*]. M. Schollmeier et al. used miniature quadrupoles whereas T. Toncian et al. controlled the beam with the help of a laser-driven electrostatic micro-lens. In both experiments the beam was refocused after collimation to a very small focus spot size, about 200 µm in diameter, but the number of protons in the bunch reached only 10^6 and 10^8 particles respectively.
Experiments at the JETI system have shown for the first time that quasi-monoenergetic proton pulses could be generated from thin solid targets with specially prepared micro-structures on the target rear surfaces [*3.6*]. With an enhanced procedure for alignment and target preparation the reproducibility of the generation of proton beams showing quasi-monoenergetic features in their spectrum could be increased to a value of at least 80%. Furthermore, a first scaling law could be established for the energy of the monoenergetic peak as a function of laser energy, which was well-reproduced by numerical particle-in-cell codes [*3.7*]. Such a scaling law is essential for the reproducible production of monoenergetic ion pulses and their further application, such as the post acceleration in conventional accelerator structures as described in this proposal.
Over the last years, we have developed diagnostic systems that are capable of measuring the important beam parameters (e.g. spectrum, emittance) in single shot regime. Those have also been augmented for very high beam currents by nuclear diagnostics relying on the excitation of giant dipole resonances (GDR), an area of expertise of GSI and TUD.
Finally target fabrication and characterization is a crucial prerequisite for the proposed project. In a collaborative effort we have developed sufficient capabilities to supply the proposed experiments with sophisticated targets over the last years.

3.3) Status of simulations for collimation and transport

The laser accelerated protons require efficient collimation by a magnetic quadrupole system or a solenoid in order to reduce the large production angular spread and thus prepare the beam for further transport. In principle, simulations have to address two issues:

- *De-neutralization of the accelerated proton beam entering the collimator field:* The magnetic field of the collimator suppresses propagation of the neutralizing electrons due to their sub-millimeter gyro radius. This phenomenon may lead to modifications of the global production phase space distribution. First studies have been undertaken with the WARP-code [*3.8*].

- *Collimator effect on beam quality due to chromatic aberration:* Due to the large energy spread, chromatic aberrations of the collimator are the most serious limitation to the realistically "usable" fraction of the full particle spectrum. These aberrations cause a degradation of the transverse emittance of the "usable" fraction of protons, and the very small production emittance becomes a relatively irrelevant quantity. The studies have been carried out using TRACE3D and the DYNAMION code, with results presented at HIAT09 [*3.9*].

DYNAMION includes higher order effects in amplitudes and energy dependence as well as space charge effects. The latter are based on particle-particle interaction, which limits the space charge resolution. The tracking is carried out in the solenoid 3D magnetic field from direct integration using the coil geometry of the experimental solenoid [*3.10*]. Typical results for the final emittance due to solenoid collimation are shown in Fig. 3.1. Here it is assumed that an ensemble of particles from a fixed production cone of $\pm 10^0$ and a variable energy window between 4% and 64% around a central energy of 10 MeV is tracked. Note that beyond 32% energy width particles are lost on the assumed 30 mm radius aperture of the solenoid. Continuation of this aperture limitation by an extended beam pipe after the collimator will act as energy filter for an even smaller energy window.

Simulation predictions for transverse and longitudinal emittances after collimation and by using different energy windows shifted over the production spectrum – by varying the solenoid focusing strength – are the basis for comparison with experimental data.

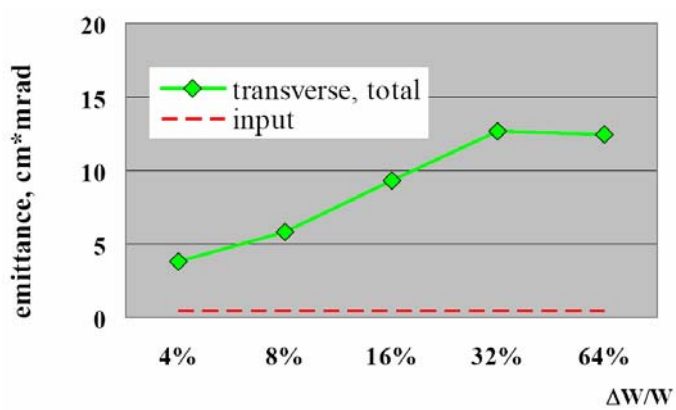


Figure 3.1: *DYNAMION simulation: actual bunch emittance as function of energy spread around 10 MeV showing onset of loss on solenoid aperture*

References

[3.*1*] *K. Harres et al., Phys. Plasmas 17, 023107 (2010)*
[3.*2*] *M. Schollmeier et al., Phys. Rev. Lett., 101, 055004 (2008)*
[3.*3*] *T. Toncian et al., Science 312 (5772), 410–3 (2006)*
[3.*4*] *S. Ter-Avetisyan et al., Laser Part. Beams, 26, 637 (2008)*
[3.*5*] *Nishiuchi et al., Appl. Phys. Lett., 94, 061107 (2009)*
[3.*6*] *H. Schwoerer et al., "Laser–plasma acceleration of quasi-monoenergetic protons from microstructured targets", Nature 439, 445 (2006)*

[3.7] *S. Pfotenhauer et al., "Spectral shaping of laser generated proton beams", New Journal of Physics 10, 033034 (2008)*
[3.8] *F. Nürnberg, Capture and control of laser-accelerated proton beams: experiment and simulation, Proceedings o the 23rd Particle Accelerator Conference, Vancouver BC, Canada (2009), Journal of Physics: Conference Series, 244, 022052 (2010)*
[3.9] *I. Hofmann et al., Proc. HIAT09, Venice, June 6-9, 2009*
[3.10] *M. Droba, private communication*

4. Layout / Setup

4.1) The test stand for laser-accelerated ions at the Z6 experimental area

Figure 4.1 shows an overview of a part of the experimental hall at GSI with the Z6 and Z4 stations, as well as the transfer line from the GSI UNILAC (UNIversal Linear ACcelerator) to the SIS 18. This area has been used for combined PHELIX long pulse / ion beam experiments since 2007 which means that only minor efforts need to be made in terms of laser and radiation safety as well as the clean room environment necessary for the laser. The project described here will use a sub-aperture beam of the full PHELIX long pulse beamline which will be recompressed by a newly set up vacuum compressor. The compressed laser pulse (see table 4.1 for parameters) will be guided under vacuum to the existing target chamber which is already equipped with a vast range of plasma diagnostics. An off-axis parabola with short focal

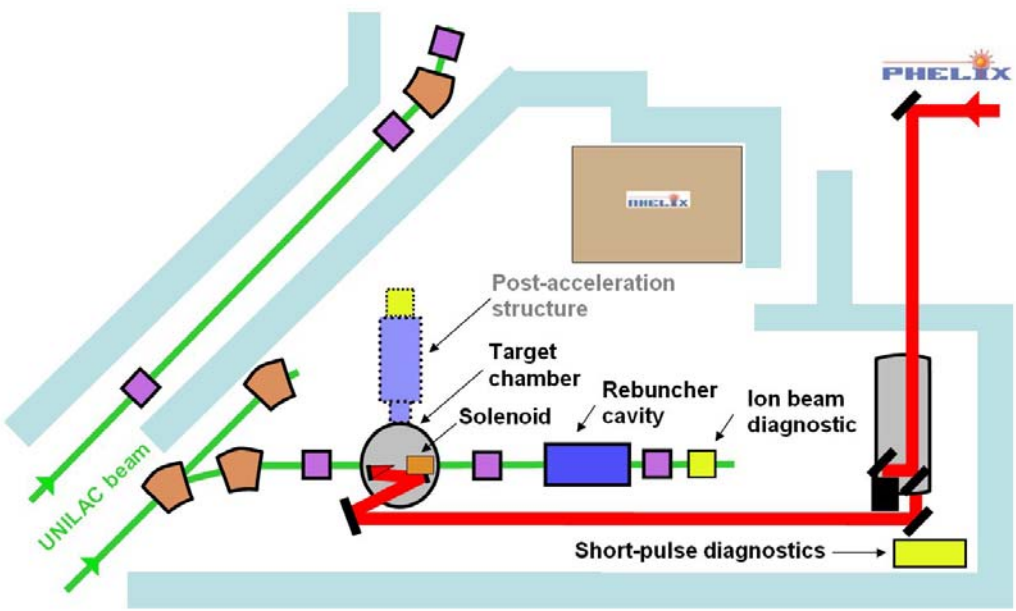


***Figure 4.1**: Overview of the Z4 and Z6 experimental areas*

distance is used for focusing the laser beam onto the targets. This setup can easily be modified to emit the proton beam either in the horizontal direction in figure 4.1, along the axis of the ion beam coming from the UNILAC, but perpendicularly to this direction as well which is useful for the injection into larger structures.

Beam diameter	120 mm
Wavelength	1053 nm
Pulse duration	500 fs
Pulse energy	50 J
Repetition rate	1 shot every 50 min
Intensity in focal spot	10^{19} W/cm^2

Table 4.1*: Parameters of the laser beam*

4.2) Compressor and 100 TW beamline

As can be seen in figure 4.2, the compressor housing is placed below the beamline which delivers the full-aperture (28 cm) PHELIX beam to the Z6 target area. The beam diameter will be decreased to 12 cm by inserting an appropriate aperture in the PHELIX frontend and preamplifier which allows using smaller optics for guiding the laser beam through a window into the compressor. The inset of figure 4.2 shows how

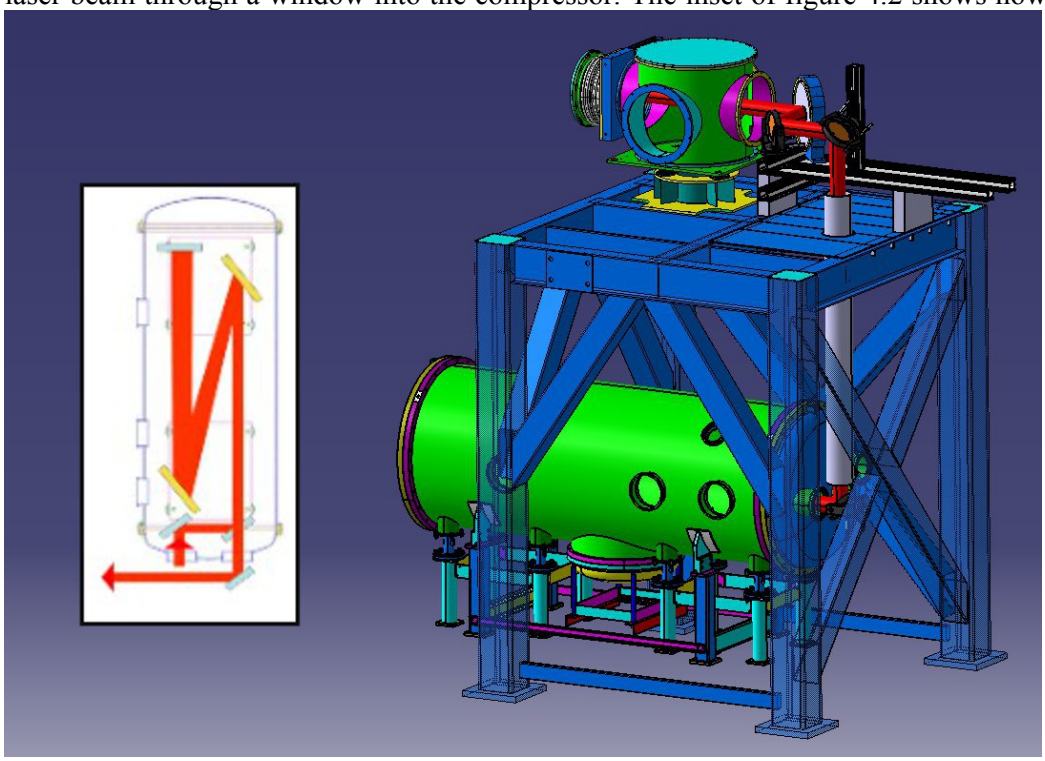


Figure 4.2: Construction sketch of the beam path into the vacuum compressor with an inset showing the optical compressor layout.

the beam is compressed in two steps by passing twice over the pair of gratings with an intermediate 0° mirror. The separation of the incoming and the outgoing beam is achieved by slightly tilting this mirror vertically so that the output beam is shifted higher and can pass above the injection mirror. A set of short pulse diagnostics developed by the Helmholtz Institute Jena will be installed to monitor the pulse parameters. Due to deterioration of such a high-intensity beam in air, it is necessary to guide the pulses in a vacuum beamline to the target chamber, as shown in figure 4.3.

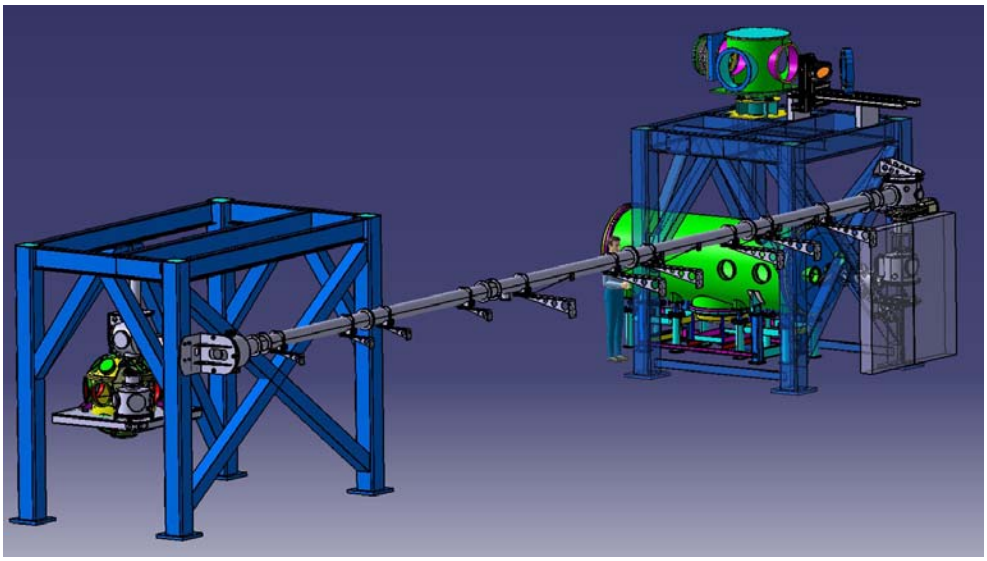


Figure 4.3*: Construction sketch of the beamline between the compressor and the target chamber.*

4.3) Beam dynamics layout

The beam line includes the following elements:

1) **Pulsed solenoid as collimator**: The magnetic field rises in a ramp to a maximum value of ~15 Tesla. The variable field strength is used to focus different energies into the RF cavity respectively diagnostics devices.
2) **Beam pipe for debunching**: The 3-cm radius pipe with length 250 cm has an energy transmission of approximately 20% (fwhm) at the reference energy of 10 MeV. The drift length is determined by the need for debunching of the particles with ±4% energy width to a length corresponding to approximately $\pm 60^0$ phase width in the RF bucket (±1.5 ns). By using a ~1cm radius diaphragm (placed before the RF cavity) the energy filtering can be narrowed down to contain primarily particles from the ±4% energy window matched to the bunch rotation.
3) **RF cavity for bunch rotation:** Bunch rotation at 500 kV and 108 MHz frequency (synchronous phase -90^0), which decreases the energy width of the ~±4% core to <±0.5%. As the pipe will always transmit also off-energy particles – here about 20% fwhm - neighboring buckets will lead to a modulation of these particles without changing much their energies (details on bunch rotation see Chapter 9.2)
4) **Diagnostics:** Time (bunch) resolved transverse diagnostics is carried out with a streak camera, which requires a plastic scintillator faster than 100-200 ps. For transverse (time integrated) emittance measurements a pepper-pot device is used. The disturbing background of off-energy particles (outside of the ±4% energy window) is minimized by a ~1cm diaphragm**.** Longitudinal current profiles are measured by phase probes. The successful bunch rotation minimizes the energy spread of the core. This core then expands at a much lower rate than the rest of the beam, which can be verified using phase probes at different distances behind the cavity. Eventually additional (to the solenoid) transverse re-focusing optics (quadrupole triplet) might be needed to avoid beam size blow-up.

Using the calculated field data of the solenoid applied in the first PHELIX experiments, we compare in Fig 4.4 characteristic rays of protons produced in the energy window of ±4% with those from ±64%, both around a central energy of 10 MeV and using an opening angle of $\pm 10^0$ (DYNAMION simulation). It is noted that the solenoid field forms a focus of the energy window of ±4% at the location of the RF cavity, which is easily obtained by slightly adjusting the solenoid field. The broad ±64% energy window is to a large extent (60-70%) lost on the beam pipe, which therefore acts as energy filter.

Simulations of the bunch rotation with 500 kV and 108 MHz for an ensemble with ±64% initial energy spread from the source are shown in Fig. 4.5. Note that the momentum distribution is plotted versus $dp=\Delta p/p \sim 0.5\Delta E/E$ and the phase deviation from -600^0 to $+600^0$, which includes > 3 RF periods. The top frames show the distribution just before rotation and after beam tube energy filtering; the bottom frames after bunch rotation (ignoring space charge effects). Particles in neighboring bunches are only slightly collimated in momentum as indicated by the two small satellites (bottom left).

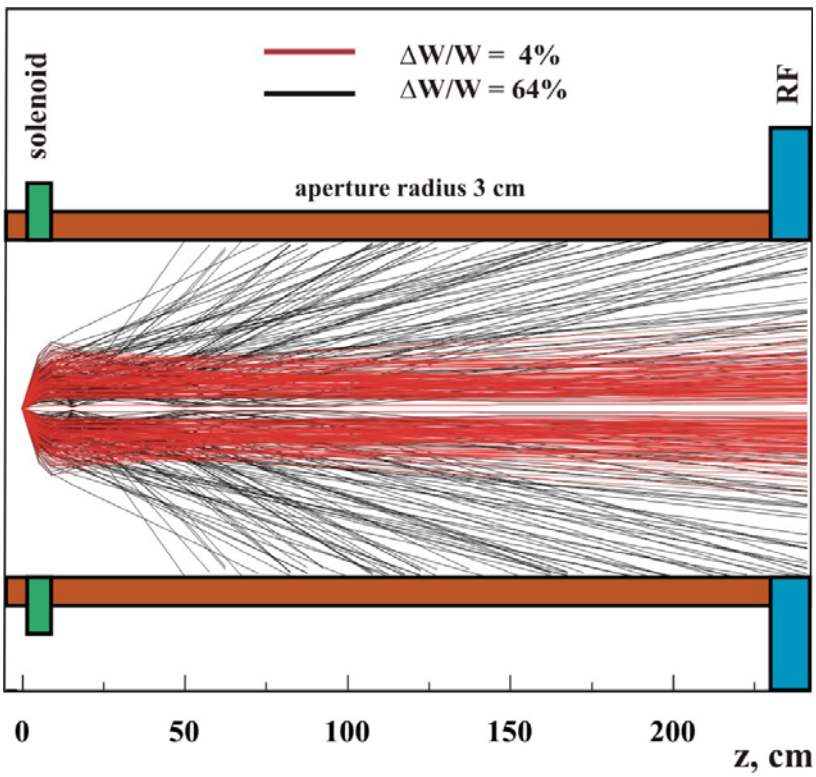


Figure 4.4: *Rays of protons from source to RF cavity through 3cm radius beam pipe, comparing narrow and broad energy windows*

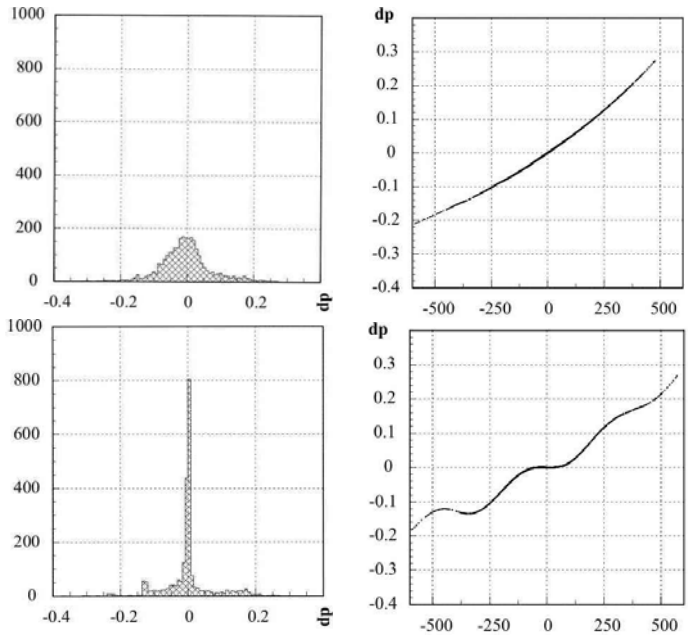


Figure 4.5: *Input momentum distribution plotted versus Δp/p (top left) and input longitudinal phase space plotted versus the phase deviation in degrees (top right) into RF cavity, compared with result after bunch rotation (bottom).*

The following parameters characterize the complete spectrum of particles as well as the **"reference bunch"** after the drift, which is defined to contain particles within the ±4% energy window suitable for bunch rotation and a 50 π mm mrad reference acceptance. After bunch rotation both the emittance and momentum spread of this reference bunch would match for hypothetical injection into the SIS synchrotron at GSI. Note that by adjusting the solenoid field strength a waist of <1cm radius is produced for this "reference bunch" in the area of the RF cavity and the diagnostics devices. If needed, use of a ~1cm radius diaphragm could minimize the "background" of protons not belonging to the reference bunch.

	intensity	ΔE/E	ε π mm mrad	bunch duration ns (full length)	beam radius cm
assumed total production at source	~ 10^{13}	~100%	<1	<0.001	-
transmission through pipe	~ 10^{12}	20% (fwhm)	~150	~25	3
after bunch rotation	~ 10^{12}	<1% (fwhm)	~150	~25	3
"reference bunch" (after rotation)	2 10^{9} (35 mA)	<0.5% (full)	50	~3	<1

Table 4.1: *Parameters of a "reference bunch" at 10 MeV, compared with transmission through 250 cm long pipe (3cm radius) and total production at source.*

CH tank post-acceleration: In an advanced stage the target chamber (and solenoid) will be rotated to the "post-acceleration" structure shown in Fig. 4.1 to provide the CH cavity unit with beam, it requires a much shorter drift due to the 3 times higher RF

frequency of 325 MHz and allows acceleration from 11.7 to 24.3 MeV (details see appendix).

5. Experimental program

Based on the first experimental campaigns to transport a laser accelerated ion beam performed at the PHELIX laser bay area we intend to extend the work at Z6, where, besides additional laser beams and diagnostics a fully equipped ion beam line is available. We intend to use improved versions of the solenoid magnet based on the detailed analysis of the first experiments and inject the beam into the Z6 ion beam line. This can be achieved by the use of a special pulsed high field solenoid with an opening diameter of 40 mm, operating at magnetic flux densities of more than 12 T. The solenoid was designed to resist the very high magnetic pressures of tenth of MPa during operation.

A first solenoid was successfully tested in the high-field laboratory of the Forschungszentrum Dresden concerning its field strength and durability. The required electrical power is provided by a standalone pulser system which has already been developed and is currently tested at PHELIX. This easily allows reaching the maximum field strength in the solenoids at the time the proton beam is going through. A current of 13.5 kA at 16 kV is necessary to obtain a field of 12 T in the solenoid.

The initial measurement and the analysis of the proton beam is done by radiochromic films in stack configuration and a Thomson parabola spectrometer with an MCP for an online measurement. The Thomson parabola gives information about the accelerated ion species, their charge states, energies and spectra. Radiochromic films are dosimetry films that provide the energy as well as a space resolved measurement of the ion beam with high spatial resolution. The stack configuration delivers information about the position of the focal spot as well as its size with micrometer resolution and allows observing space charge affects caused by the high flux of the beam that can lead to a broadening of the envelope. The solenoids are perfect energy filters due to the applied voltage but also as result of chromatic aberrations, these influences can be investigated by using RCF in special stack configurations.

Since the half opening angle of the proton beam is quite large (up to 30°) besides the flat foils special hemisphere targets will be used to reduce the opening angle directly at the beam origin at the target surface. The benefit is not only the more collimated beam but also the required field strength of the solenoids for the desired energies can be reduced so that even higher energies can be collimated.

Within this experiment the proton beam parameters after collimation need to be investigated. Especially information about the beam emittance will be collected. The emittance is very important for further transport and focusing or for any injection device into a conventional accelerator. Hence, a pepper-pot will be used for the beam characterization.

Additionally, to reach a better understanding about the propagation of the protons through the solenoid the electron spectrum needs to be analyzed. After the creation at the target rear surface the beam is quasi-neutral due to the co-moving electrons at the same speed at the protons. These electrons are strongly deflected by the solenoid field and around half of them get forced down to the solenoids axis circulating at their gyro radius around the solenoid's axis. The other electrons are reflected due to the magnetic mirror caused by the fringe fields of the solenoid. These effects influence the transport of the protons through the solenoid. Detailed information about the co-moving electrons is used as input parameters for particle in cell calculations. First results

indicate that the space charge of the electrons inside the solenoid will lead to density modulations of the protons with a maximum on the solenoid's axis which causes a stronger focusing effect.

Future experiments will be carried out at the experimental stations Z4 and Z6. The new 100 TW system provides a laser beam which perfectly fits the desired parameters to produce a high flux proton beam at the needed proton energies of 10 or more MeV. The solenoid will be installed directly in the Z6 target chamber which is equipped with several diagnostic tools as e.g. a multi frame interferometry. The bunch-rotation device can be included in the already existing ion beam line at Z6 or can be installed as a stand alone experiment with a new connection to the target area. At Z6 several ion beam diagnostics will be installed for a full 6D beam characterization to show that the laser-accelerated protons fulfill needs for further transport or injection into a conventional post accelerating stage.

Reproducibility studies

The acceleration mechanism based on TNSA is known to be quite stable and reproducible within a given experimental setup. However due to the limit of available repetition rate the experimental database is limited. We intend to fully use the synergy of having a high power laser system at GSI (PHELIX) as well as high rep rate systems at the participating institutes (JETI, POLARIS in Jena, DRACO in Dresden). Hence we will investigate the ion injection at PHELIX, the ion beam production at JETI and POLARIS and the reproducibility of the combination at lower particle energies (or numbers) at the DRACO system, where the Forschungszentrum Rossendorf is developing a high rep rate pulsed solenoid for ion injection. This will be combined with the diagnostics development at GSI for the ion beam and the target production development at TU-Darmstadt.

6. Technical components

6.1) Laser system

The laser system used for this project consists of the PHELIX short pulse front end, preamplifier and main amplifier sections and the dedicated compressor installed at the Z6 area. It is based on the scheme of chirped pulse amplification in flash lamp-pumped Nd-doped glass which allows producing high-energy pulses with pulse durations around 500 fs, however, due to the heating up of the optical components, the repetition rate is limited to about one shot per hour. Special care must be taken to ensure the appropriate synchronization of the laser system with the RF system for the buncher cavity (see ch. 6.4) because the generated particle beam has to enter the oscillating field with the right phase with a precision of +/- 0.5 ns. This will be ensured by the installation of a frequency synthesizer unit which can synchronize the PHELIX fs front end oscillator to the RF frequency of the cavity power supply.

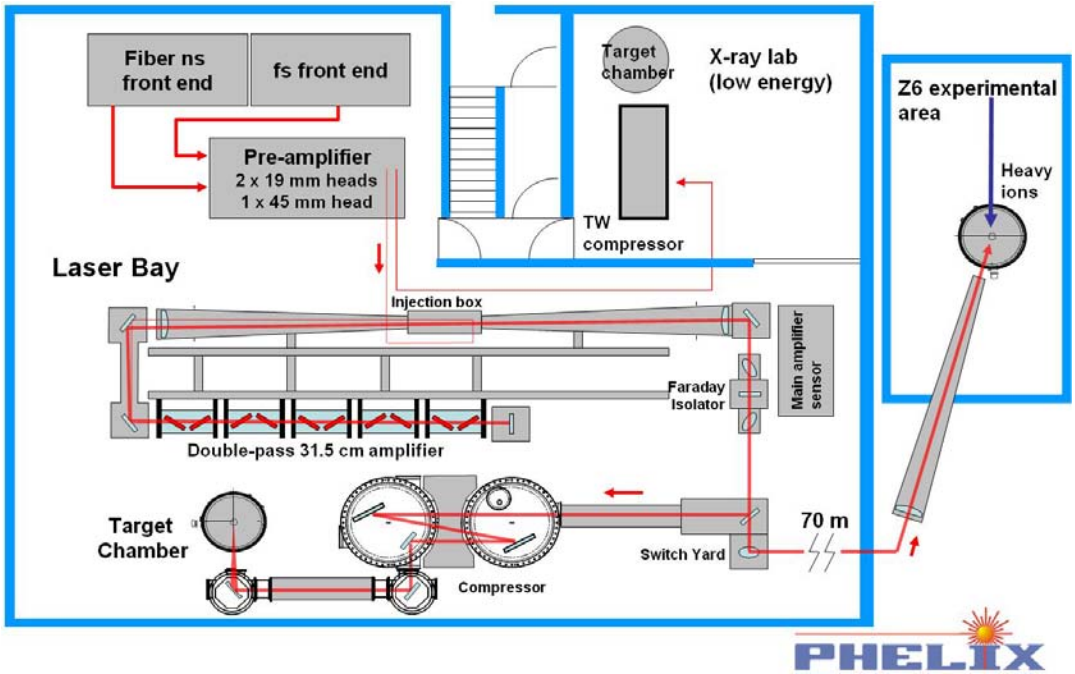


Figure 6.1*: Schematic overview of PHELIX*

6.2) Targets

The Target Laboratory at the University of Darmstadt has previously provided various types of 3d target geometries for fundamental research experiments with laser and particle beams at high energy densities.

Amongst others have been targets, such as conventional gold hohlraum cavities for radiation confinement studies, hemispherical targets (Fig. 6.2) and structured foil targets for the experimental investigation in the realm of laser induced ion acceleration and ion focusing and targets dedicated to warm dense matter experiments in a pump probe scheme by means of X-Ray Thomson scattering (Fig. 6.3).

Figure 6.2: *"Hohlraum targets"*

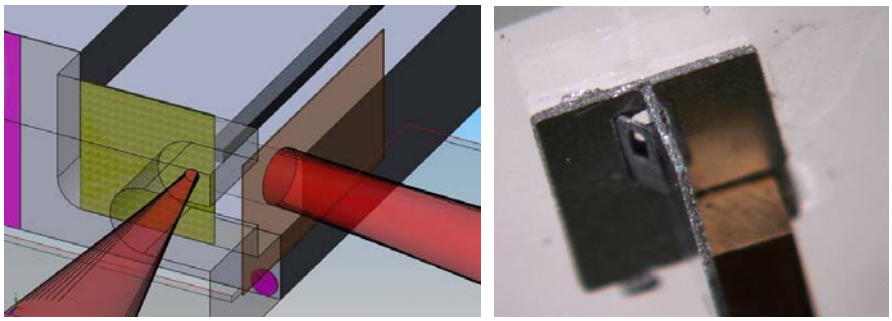


Figure 6.3: *Scheme and image of the X-Ray Thomson scattering setup*

With respect to ion focussing experiments, we currently work on optimising the target layout to generate an ion beam with well defined parameters in terms of particle number, energy spread and beam emittance. The latter is to be further specified with respect to focus diameter and position for targets utilizing a geometry which promotes ballistic and / or focussing by electromagnetic fields.
As for experiments which investigate the feasibility of focussing the beam with a specifically shaped target, we have proposed several different designs and manufacture targets such as:

a) Hemispherical targets made from gold with different wall thicknesses in the range of 5µm to 25µm and different radii of curvature in the range of 200µm to 500µm.
b) Spherical gold targets of different fill factor - a sphere cut at different degree of latitude.
c) A Plane foil target for ion acceleration in combination with a cone to promote focussing.
d) A spherical target for ion acceleration combined with an adjacent cone.
e) Cone targets of several different opening angles with straight walls.
f) Cone targets with an either concave or convex wall shape.

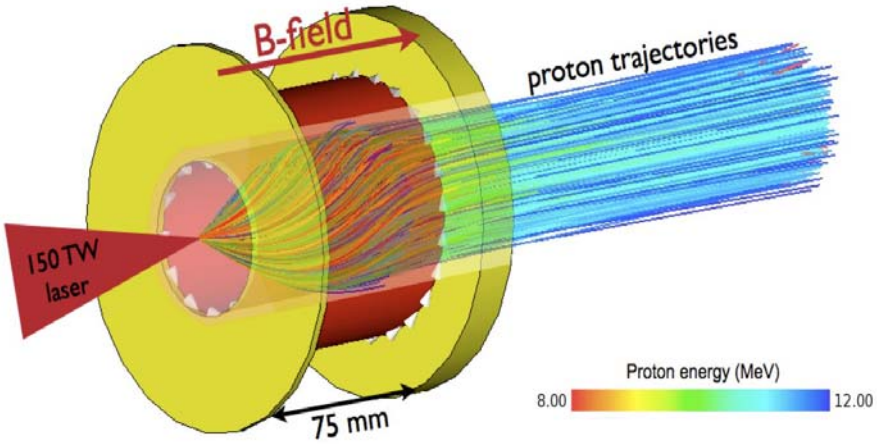
In addition to providing well proven target solutions for ongoing experiments at high intensity laser systems in Europe, USA and Japan, we are determined to develop process know-how and production capabilities amenable to high number target production and high repetition rate experiments respectively.

6.3) Solenoid

The most challenging task is the interface between the laser-ion accelerator and conventional ion optics. The beam shows an exponential particle spectrum with an energy spread of 100% and is strongly divergent with energy dependent half opening angles up to 25 degrees. Therefore, the first step is to collimate the beam.

This will be done by a strong pulsed solenoid with a high magnetic flux density. Several solenoid versions have been designed by the Institut für Strahlenphysik and constructed by the Institut für Hochfeld-Magnetlabor in Dresden. An earlier version that was used in the PHELIX beam time in late 2009 and 2010 is composed of 4 layers of 27 turns per layer, see figure 6.4 center of bottom line. This 108 turn (in total) coil has an inner diameter of 48 mm, and the first layer of Cu windings has a diameter of 54 mm. The length of the windings is 150 mm resulting in an inductance of ~250 µH. The multiple layers increase the field homogeneity and, as compared to

shorter coils, the length increases the focusing power resulting from the increase in azimuthal velocity. The solenoid was commissioned at FZD with multiple 16 kV, 16 kA (Bmax ~ 14 T) pulses with a rise time of 400 µs and a fall time exceeding 1.0 ms with no change in structural integrity and a temperature rise of ~6 °C per 16 kA pulse. With the present PHELIX capacitor set-up yielding a maximum current of 10 kA through the lens, the maximum proton energy that can be collimated according to General Particle Tracer is 18 MeV and the maximum full capture angle is near 30 degrees for a coil-to-target distance of 95 mm.



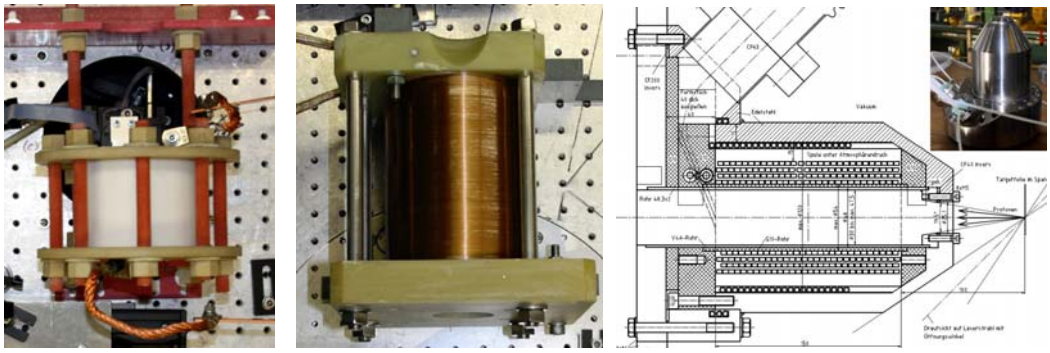


Figure 6.4: *CST-Particle Studio simulation of the solenoid with calculated proton trajectories at 10 MeV for the PHELIX experiment. The images below show the different generations of solenoids.*

The inclusion of an Al or Cu plate on axis and near the target allows for the superposition of magnetic fields resulting from both the solenoid and the Eddy currents within the plate. This results in a reduced total field behind the plate (e.g. the field at a target-to-coil distance of 50 mm is reduced by 93% at the target by the inclusion of a 3 mm thick Cu Eddy-shield centered between the two (as shown by COMSOL simulations).

Reflecting laser light off an 80 mm diameter, 13 µm thick Al-foil target onto a 2-D position sensitive diode showed an elimination of target movement in the presence of an Eddy-shield (target-to-coil distance of 100 mm). Further field reduction is possible when the entire coil is properly enclosed within a conductive media.

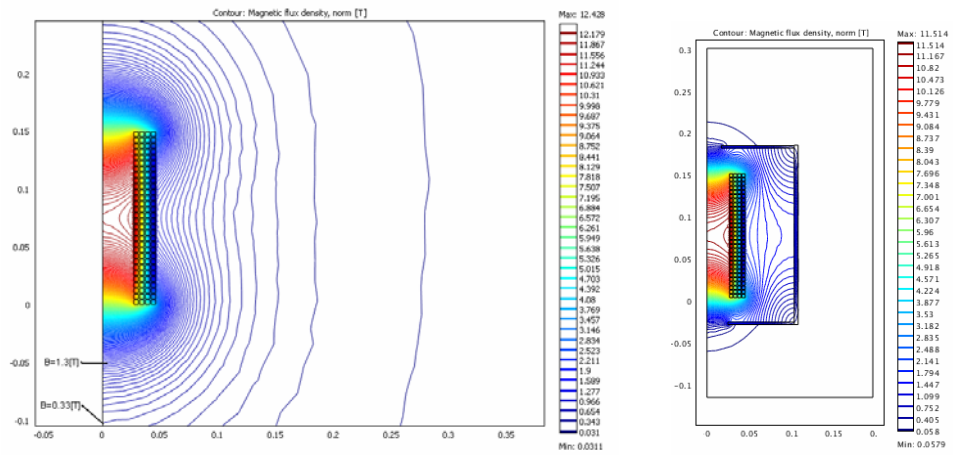


Figure 6.5*: COMSOL simulations of the magnetic field distributions without (left) and with (right) Eddy current shielding.*

6.4) RF buncher cavity

With an operation frequency of 108.408 MHz (9.22 ns period) in mind the following solution is proposed:

1. Use of an existing cavity with a single spiral (two gaps, 250 kV max. each) with the following specifications:

- Resonance frequency 108.4 MHz
- Inner tank diameter 500 mm
- Inner tank length 540 mm
- Aperture 50 mm
- N_{target} (at U_0 = 1 MV) 100 kW

2. Sharing of an existing RF amplifier (location UNILAC RF gallery) which is occasionally used for supplying the RF chopper BC3 in the TK. The components for this 'shared mode' are mostly available. The RF energy cable and the corresponding tank output couplers are switched to the respective tank via a coaxial switch or relay. The control of the switching process should be realized via the GSI control system.

3. The following system parts would have to be purchased or modified:
Plunger piston control, switching electronics, personal safety interlock, UNILAC timing, RF regulator system

4. Boundary conditions and costs
Synchronization with the PHELIX system needs to be taken care of. Furthermore, it has to be confirmed that the present regulation precision (0.5% in amplitude and 0.5° in phase) is sufficient. The shared use of the RF amplifier has to be taken into account in the beam time planning. Since mostly existing components are to be used, the costs are estimated to be around 50 k€.

Since, from the point of view of RF installations at the linear accelerator, the laser ion acceleration appears to be a de-centered system, a dedicated RF system close to the experiment would be a better, however, more costly solution.

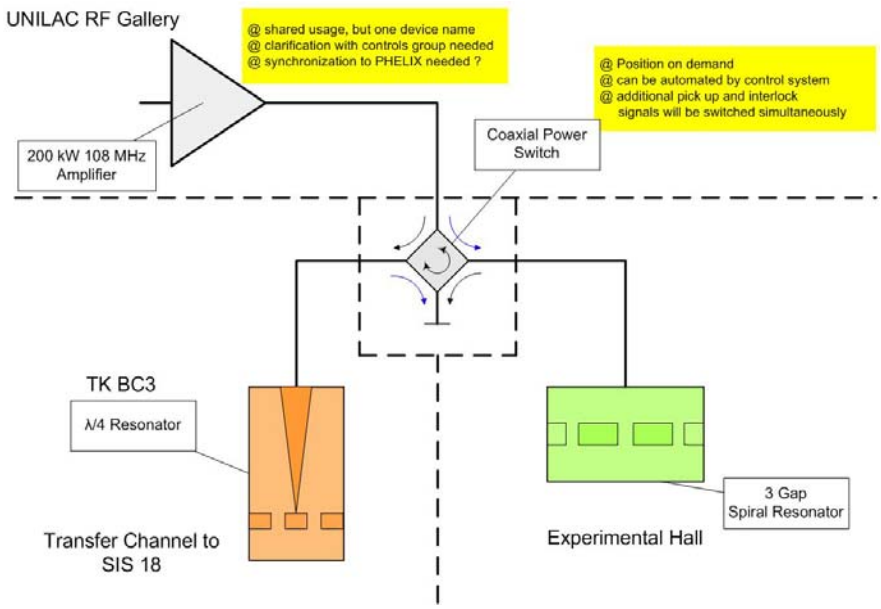


Figure 6.5: *Schematic view of the HF supply*

Because of recent RF installations at the HITRAP facility, RF spare amplifiers in the power range of 200 kW are depleted, so this would imply the purchase of an independent RF system of the power mentioned above, including all additional components (supply unit, LLRF, interlock system, connection to GSI control system etc.). This approach would, in coordination with the vendor of the cavity, bring the advantage of the free choice of the operating frequency. The estimate of the cost would be about 550 k€ without the cavity.

6.5) Diagnostics

Whereas the measurement of the transverse beam emittance within a single shot seems feasible with existing instruments, R&D work will be necessary to allow for measurements of the longitudinal phase space in single pulses containing a broad range of energies.

Transverse beam emittance measurement

For the single-shot measurement of the transverse beam emittance a "pepper-pot" setup is foreseen. A conventional slit-grid system may not be used due to the low repetition rate. A pepper-pot emittance meter was built for high current emittance measurements at the GSI UNILAC [*6.1*]. The ion beam penetrates a plate with a regular matrix of apertures. The beam spots of the transmitted ions ('beamlets') are detected using a scintillating screen. This image is recorded by a CCD camera. With the assumption that the aperture holes are point-like and the knowledge of the distribution of the scintillation on the screen material the transverse emittance can be calculated from geometrical parameters only [*6.2*]. This setup allows the measurement of the transverse emittance within a single macro pulse.

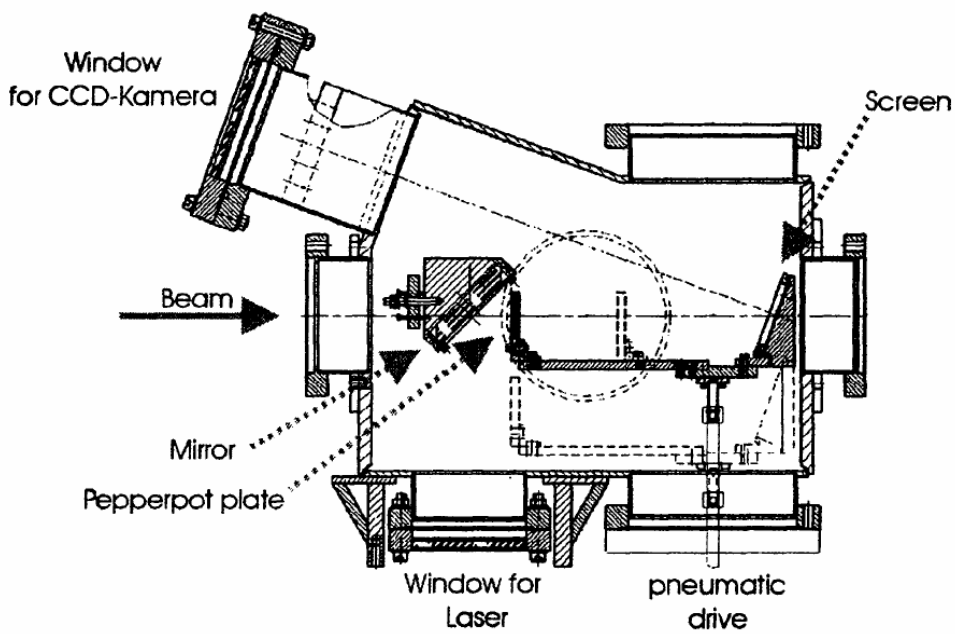


Figure 6.6: *Schematic drawing of the existing pepper-pot system; the whole setup can be moved into the beam axis by a pneumatic drive. For calibration a mirror inflects a laser beam onto the screen.*

In the existing setup (Fig. 6.6) a 45x45mm^2 copper plate with 15x15 holes of 0.1 mm diameter is used. The beamlets are stopped behind a variable drift of 150-250 mm on a Al_2O_3 screen. The divergence of the beam is calculated with respect to the image of the pepper-pot pattern. This image is created on the screen with a HeNe laser, which illuminates the pepper-pot plate via a mirror mounted on a pneumatic drive. The laser image is used for calibrating the device to reduce mechanical uncertainties. In addition the interior of the chamber is blackened in order to reduce errors caused by light reflections. The selection of scintillating materials with respect to light yield and correct profile reproduction are subject of ongoing R&D studies in the beam diagnostic department [*6.3*]. With the PC controlled fast shutter CCD camera a resolution of less than 0.5 mrad in divergence at a spatial resolution of 0.1 mm has been achieved. A screenshot of a pepper-pot measurement with a high current Ar^{1+} beam at 1.4 MeV/u is presented in Fig. 6.7 as well as the projection of the horizontal plane.

For further optimizations detailed studies on various scintillating materials are necessary: Recently an incomprehensible dependence of the beam width (as measured with a scintillating screen) from the screen material has been reported [*6.3*]. In order to improve the angular and/or spatial resolution of the setup different pepper-pot materials have to be studied, e.g. tungsten or tantalum foils with varying hole distances.

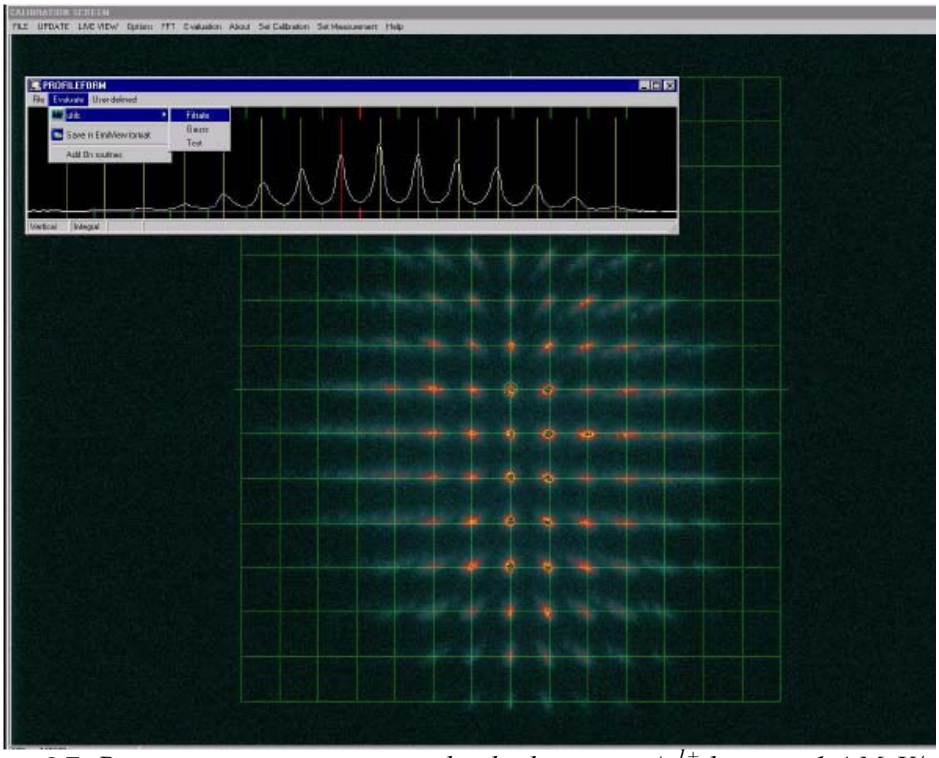


Figure 6.7*: Pepper-pot measurement with a high current Ar^{1+} beam at 1.4 MeV/u*

Measurement of the longitudinal phase space

More detailed investigations are necessary for the development of measurement setups for longitudinal beam parameters, i.e. bunch length and energy distribution. One possible starting point is a device similar to the bunch shape monitor installed in CERN Linac 2 [*6.4*]. Here secondary electrons emitted by the impinging ion beam on a wire held on negative potential are detected using a secondary electron multiplier. A pair of RF-deflector plates deflects the secondary electron beam and with a moderate drift length of 0.5 m this device reaches a time resolution in the range of several picoseconds. For the single-shot measurement of the beam energy a combination of a magnetic spectrometer with a beam-induced fluorescence monitor equipped with a streak camera could be used. At first the spectrometer translates the energy to a space distribution and transports the beam to a beam induced fluorescence monitor. This device consists of a differentially pumped vacuum chamber with blackened walls. The chamber can be moderately pressurized with a working gas, e.g. noble gas. The passing ion beam ionizes the working gas and light emitted by the ionized gas atoms is recorded using a high resolution streak camera. GSI has good experience with beam induced fluorescence monitors installed in the UNILAC and high-energy beam transport section [*6.5*], but adopting the setup to the requirements for laser-accelerated ion beams and including the spectrometer stage is a challenging R&D project.

References

[*6.1*] *T. Hoffmann et al., "Emittance Measurements of High Current Heavy Ion Beams Using a Single Shot Pepperpot System", Proceedings Beam Instrumentation Workshop 2000, Cambridge AIP Vol. 546, p. 432 (2000)*

[*6.2*] *J. Pfister et al., "Single-shot emittance measurements at HLI and HITRAP" GSI Scientific Report 2007, Darmstadt, p. 292 (2008)*

[*6.3*] *E. Gütlich et al., "High Current Ion Beam Investigations on Inorganic Scintillation Screens", Proceedings DIPAC09, Basel, p. 167 (2009)*
[*6.4*] *A. V. Feschenko, Proc. Part. Acc. Conf. PAC2001, Chicago, p. 517 (2001)*
[*6.5*] *F. Becker et al., "Beam Induced Fluorescence Monitor & Imaging Spectrography of Different Working Gases", Proceedings DIPAC09, Basel, p. 162 (2009)*

7. Cost and Resource plan

Table 7.1 gives a representation of the distribution of the work load amongst the project partners. The contribution from PhD students naturally occurs in the frame of and in accordance with their respective thesis subjects. The given FTE (full time equivalent) numbers are meant to give an estimate of the annual contribution of a project partner which usually will be coming in part from several scientists or engineers.

Partner\Year	**2010**	**2011**	**2012**
TU Darmstadt	1 FTE, 1 PhD	1 FTE, 1 PhD	1 FTE, 1 PhD
GSI Plasma Physics	2.5 FTE, 1 PhD	2.5 FTE, 1 PhD	1 PhD
GSI Atomic Physics	1 PhD	1 PhD	1 PhD
GSI Accelerator	0.5 FTE, 1 PhD	0.5 FTE, 1 PhD	
Helmholtz Inst. Jena	1 FTE, 1 PhD	1 FTE, 1 PhD	0.5 FTE
FZ Dresden-Ross.	1 FTE, 1 PhD	1 FTE, 1 PhD	
U Frankfurt	1 FTE, 1 PhD	1 PhD	

Table 7.1*: Human resource overview of the project*

In addition to the cost estimates given in table 7.2, the corresponding funding sources are shown in table 7.3. About 112 kEUR coming from a BMBF project and 200 kEUR from a Virtual Institute (VI-144) were already invested in the acquisition of optomechanical components and optics for the compressor and the laser beamlines, as well as about 30 kEUR for the development of the 100 TW beamline coming from GSI Plasma Physics and Helmholtz Institute Jena.

Task\Year	**2010**	**2011**	**2012**
Laser timing / laser beamlines including vacuum, compressor optomechanics, short pulse diagnostics, focusing	180 kEUR	25 kEUR	
Modification of the existing proton beamline	15 kEUR	20 kEUR	
Installation of the RF cavity infrastructure	5 kEUR	45 kEUR	
Ion beam diagnostics	20 kEUR	60 kEUR	5 kEUR
Solenoid and power supply development	20 kEUR	20 kEUR	10 kEUR
Consumables (spare parts, targets, detectors)	20 kEUR	20 kEUR	40 kEUR
Sums per year	260 kEUR	190 kEUR	55 kEUR

Table 7.2*: Investment and consumable plan of the project*

Contributor\Year	**2010**	**2011**	**2012**
Helmholtz Institute Jena	100 kEUR	100 kEUR	35 kEUR
EURATOM	50 kEUR		
GSI PP/PHELIX	100 kEUR	80 kEUR	20 kEUR
GSI Atomic Physics	10 kEUR	10 kEUR	
Sums per year	260 kEUR	190 kEUR	55 kEUR

Table 7.3*: Funding commitments from the respective partners*

8. Time plan

Table 8.1 represents a rough time schedule. The first two phases deal with the setup of the laser infrastructure as well as the setup and experimental commissioning of the proton source part and the bunch rotation cavity. The third phase, starting in the first quarter of 2012, contains several extended experimental campaigns during which the system can be optimized and systematic parameter scans can be performed.

	Task	**Finished**	**Responsible**	**Participants**
Phase 1	Design and setup of the beamline to the compressor	09/2010	HIJ	HIJ, PP, PH
	Design, setup and testing of the compressor	11/2010	HIJ	HIJ, PH
	Design, setup and testing of the short pulse diagnostics	10/2010	HIJ	HIJ, PH
	Setup of the beamline between compressor and target chamber	11/2010	HIJ	HIJ, PP, PH
	Laser focalization and target setup	12/2010	PP	HIJ, PP
	First acceleration experiments	01/2011	TUD	TUD, HIJ, PP
	Ion beam diagnostics setup	02/2011	PP	ACC, HIJ, PP, AP
Phase 2	Setup of the pulsed solenoid	03/2011	FZDR	FZDR, PP, TUD, PH
	First laser accelerated proton beam transport experiments	04/2011	TUD	TUD, HIJ, PP
	Installation, commissioning and maintenance of the bunch rotation cavity	10/2011	ACC	ACC, PP, AP
	Injection of laser accelerated protons into the bunch rotation cavity	02/2012	TUD	TUD, ACC, HIJ, PP
Phase 3	Measurements of ion transport and characteristics of the ion beam	12/2012	TUD	TUD, HIJ, PP

Table 8.1: *Schedule of the project and overview of the contributions to the different tasks from* ***H****elmholtz* ***I****nstitute* ***J****ena, GSI* ***P****lasma* ***P****hysics,* ***PH****ELIX engineering,* ***A****tomic* ***P****hysics,* ***ACC****elerator department,* ***F****orschungs****Z****entrum* ***D****resden-****R****ossendorf,* ***T****echnical* ***U****niversity* ***D****armstadt and* ***I****nstitut für* ***A****ngewandte* ***P****hysik at University Frankfurt*

Assuming success of the proposed experiments, two interesting extensions present themselves which, although beyond the scope of the proposal presented here, would be a logical continuation of the developments: On the one hand, a post acceleration cavity, developed as part of a new proton linac for the FAIR facility by the Frankfurt University group, is supposed to be tested with the UNILAC proton beam at the Z4 experimental area which is situated next to the Z6 area. Given the fact that the entire

infrastructure (RF, Klystrons, shielding etc.) necessary for such a test would already be set up next to the Z6 target chamber, the effort to test the possibilities of accelerating the laser-produced protons with a conventional accelerator structure should be manageable. A second option is the introduction of an adaptive optics system to optimize the laser focal spot for higher proton yield which would aim on the maximization of the focal spot intensity as well as the tailoring of specific intensity distributions, e.g. ring-shaped structures.

9. Appendix

9.1) Physical background

Acceleration of intense ion beams by ultra-intense laser fields

The development of ultrahigh-power laser systems in the last two decades has lead to increasing attention and enormous scientific activities in the field of laser-plasma interactions. In the focus of such laser beams, intensities up to 10^{22} W/cm^2 became available for experiments, and thus an entirely new area of research, the regime of relativistic plasma physics became accessible. The term "relativistic" marks the fact that electrons in the laser focus are accelerated close to the velocity of light within one half laser period, which happens for light intensities exceeding 10^{18} W/cm^2.

A wealth of new phenomena had been explored for the first time using laser light as a driver. These are for example the generation of high harmonics up to the x-ray regime, the acceleration of electrons with energies up to 1 GeV and the creation of neutrons by fission reactions. One of the most striking new discoveries was the generation of intense ion beams from laser solid interaction, see figure 9.1. Driven and initiated by energetic short pulse lasers, the beams showed a stronger collimation in the sense of an actual ion beam in contrast to the evaporation type expansion known previously from nanosecond laser matter interaction. Moreover, the ion beams were found to be emitted within a few picoseconds only, and they always were directed perpendicularly to the target rear surface of the irradiated target.

Figure 9.1: *Left: Laser-ion-acceleration from a solid target at the LLNL NOVA Petawatt laser. Right: Laser-plasma interaction at PHELIX.*

The mechanism briefly takes place as follows. Relativistic electrons accelerated by the intense laser light propagate through the target and build up a strong electric field in the order of TV/m at the rear surface of the solid. Due to the strong field strength, the atoms at the target surface are field-ionized and are accelerated in the direction of the target surface normal.

This mechanism is called TNSA (target normal sheath acceleration). The measured particle energies so far extends up to tens of MeV (60 MeV protons, 5 MeV/u palladium) and they showed complete space charge- and current neutralization due to accompanying electrons. In the experiments, particle numbers of more than 10^{13} ions per pulse and beam currents in the MA regime were observed. Another outstanding beam parameter is its excellent beam quality with a transverse emittance of less than 0.004 π mm mrad and a longitudinal emittance of less than 10^{-4} eV s.
Because of these unmatched beam characteristics a wealth of applications were foreseen immediately. Those applications range from:

- new diagnostic techniques for short pulse phenomena, since the short pulse duration allows for the imaging of transient phenomena,
- the modification of material parameters (starting from applications in materials science up to warm dense matter research and laboratory astrophysics),
- ion beam radiography and lithography,
- applications in energy research ("Fast Ignitor" in the inertial fusion energy context),
- injector of high power ion beams for large scale basic research facilities and
- medical treatment (proton and carbon therapy, transmutation of short lived radio-isotopes for positron emission tomography (PET) in hospitals).

To prosper in these exciting applications, especially for the latter one, the fusion of laser-ion-acceleration and conventional ion accelerator technology is of main importance. The establishment of this connection is the main goal of this project. GSI is a unique facility, combining a heavy ion accelerator with a laser system of the Petawatt-class, PHELIX (**P**etawatt **H**igh **E**nergy **L**aser for **I**on **EX**periments), which are the ideal conditions for such a project. The collaboration gathers top level expertise in the required fields, ranging from Ultra-Intense Laser Sciences to High Magnetic Field experience to Accelerator physics. The main goal for the new collaboration is to bring together the experts in the above mentioned field in order:

- to make a high power laser beam available at the experimental area of the GSI plasma physics group (experiment station Z6),
- to investigate the physics of ion beam generation by ultra-intense lasers,
- to explore the applications, especially in combination with secondary laser and ion beams and as a final goal
- to study the prospect of laser accelerated heavy ion beams as the next generation ion source.

Novel acceleration schemes at HIJ

A number of novel acceleration schemes have been invented and successfully tested at the Institute of Optics and Quantum Electronics, Jena (IOQ), which is an integral part of the Helmholtz Institute Jena. Inspired by conventional accelerator techniques where particle pulses are gradually accelerated in successive accelerating structures, the cascaded acceleration of proton pulses using two synchronized laser pulses impinging on two different target foils was realized [*9.1*]. In this scheme, protons showing an initially broad energy spectrum are accelerated at the first foil, and they propagate towards the second foil while undergoing longitudinal dispersion due to the different velocities. A well-defined part of the proton spectrum can then be actively manipulated by the second interaction on the second foil triggered by the second laser

pulse. A part of the proton population is post-accelerated by the electric fields arising from this second interaction. Using this scheme, it was possible to post-accelerate protons beyond their maximal energy acquired during the first interaction, again forming quasi-monoenergetic peaks in the resulting energy spectrum.
The Helmholtz Institute Jena and IOQ have two high-power laser systems at their disposal. JETI is a conventional 10-Hz Ti:sapphire system which has recently been upgraded to deliver pulses with peak powers in excess of 40 TW. The second system, POLARIS, is a fully diode-pumped CPA laser system based on Yb^{3+}-doped laser material. Reaching peak powers of currently 40-60 TW at a repetition rate of a few shots per minute, it currently holds the world record for laser-pulse peak power delivered from a fully-diode pumped system. Both systems are equipped with a large number of laser and particle diagnostics necessary for the generation of laser-accelerated ion pulses under controlled conditions. Due to their comparably high repetition rate preparatory experiments for the generation of laser-driven ion beams can be carried out in Jena. Furthermore, the testing of novel diagnostics which are necessary to characterize the laser-accelerated ion beam before feeding it into a conventional accelerator structure can be accomplished at IOQ.
Many new and promising ion acceleration schemes require an ultra-high temporal laser pulse contrast. Therefore, the JETI laser is equipped with a plasma mirror setup to lower the level of amplified spontaneous emission (ASE) from 10^{-8} to 10^{-11} in a controlled manner. Such a high contrast leads to a steep electron density gradient with scale lengths shorter than $\lambda/10$ and opens the way towards acceleration schemes beyond TNSA (c.f. below). The expertise in this intensity filtering technique can be exploited both at the POLARIS laser at HIJ and the PHELIX laser at GSI.
With ultra-high contrast a few nanometer thick foil target is still stable when the main laser pulse arrives. On those ultra-thin foil targets the absorbed laser energy is portioned to a limited mass resulting in an increase of proton energy and stability [*9.2*]. Another approach is Radiation Pressure Acceleration (RPA) where the light pressure serves for the acceleration of electrons and subsequently ions in forward direction. Circularly polarized laser pulses of ultra-high intensity contrast interacting with ultra thin foils are necessary to reach this respective acceleration scheme. Quasi-monoenergetic structures are predicted [*9.3*] and are already observed for carbon ions [*9.4*].

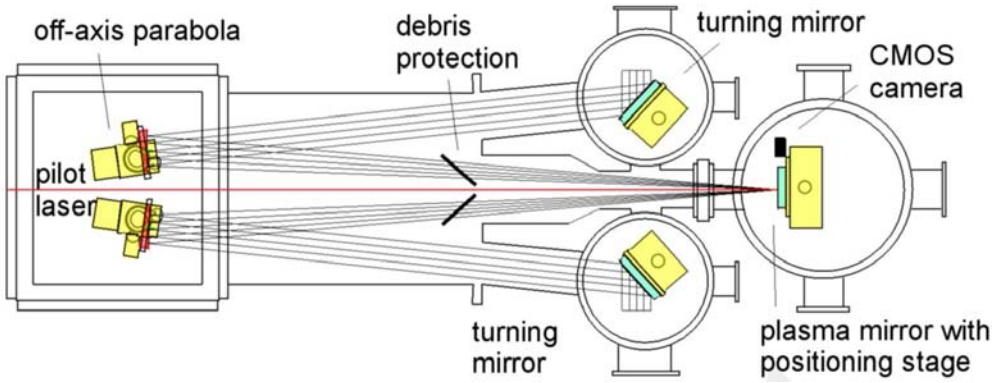


Figure 9.2: *Plasma mirror configuration which is implemented into the JETI beamline. Two turning mirrors can be electro-mechanically controlled to operate the device in bypass or plasma mirror mode. Fused silica wafers in Brewster's angle protect the off-axis parabolas to debris of the plasma mirror target. Different plasma mirror targets can be used to vary the contrast conditions: AR coated targets enhance the contrast by a factor of 1000 and blank BK7 targets by a factor of 50.*

The research at the HIJ in the field of proton and ion acceleration is also strongly focused on the development of new targets. A microstructured target delivers a proton source through a proton rich polymer structure at the backside of a metallic foil. The more homogeneous confined field strength at the position of the dot leads to a quasi-monoenergetic proton peak [*9.5*]. The polymer structures on free-standing foils or on ultra-thin foils carried by wafers are fabricated in several lithographic steps.

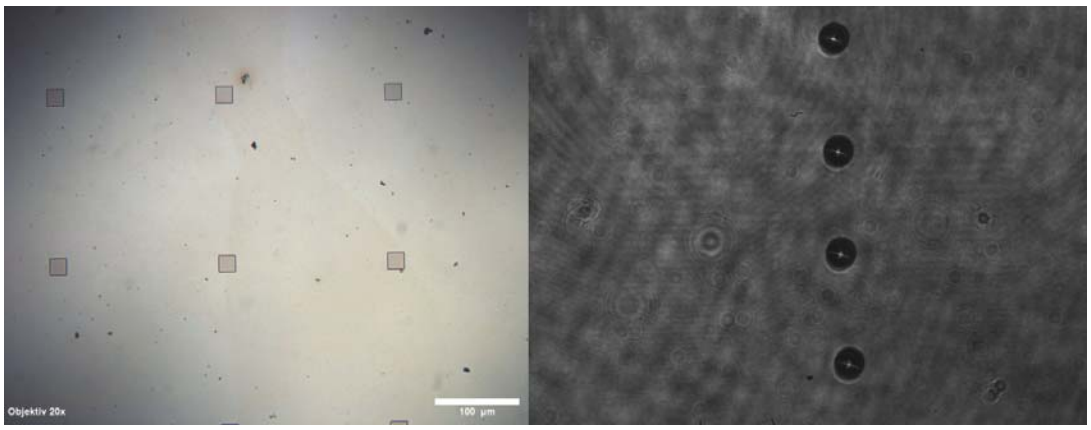


Figure 9.3: *left image: Foil target of 5µm thickness, the square dots of 10x10µm² size are 700nm thick and were produced by lithographic methods. They are composed of a polymer photoresist.*
right image: Liquid droplets, e.g. water, with a diameter of 20µm. A piezo actuator (1MHz) modulates a liquid jet to form droplets that can be synchronized with the laser.

Another approach is pursued by liquid droplets, e.g. water or deuterated water, which are very comfortable target since there is no need for shot-to-shot translations. The use of droplets of some micrometer diameter for laser-based ion acceleration has already led to monoenergetic proton beams [*9.6*]. Furthermore an additional increase of proton or ion energy has been predicted for the use of cryogenic cooled droplets. Both the investigation of ion acceleration and target fabrication is done in close collaboration with the GSI and partners at the FSU Jena.

9.2) Ion beam collimation, transport and bunch rotation

Collimation and Bunch Rotation of the Accelerated Protons

The total proton yield of typically 10^{13} particles and the observed extremely high phase space density immediately behind the source and prior to any collimator are highly encouraging. As in all cases of sources of secondary particles (antiprotons, muons, rare isotopes and others) transmission efficiency and phase space degradation due to the first collimator need to be carefully examined. In particular, higher than first order focusing properties of the collimator are a serious limitation to the realistically "usable" fraction of the production energy spectrum as well as of the production cone divergence. As these same limitations may cause a serious degradation of the transverse emittance of the "usable" protons, the very small production emittance becomes a relatively irrelevant quantity. Instead, an "effective" emittance taking into account transmission loss and blow-up caused by the collimator

should be used. In this context space charge (nonlinear) effects are a further source of emittance degradation – probably not the dominant one - to be carefully examined.

Chromatic error of solenoid collimation

In principle, pulsed solenoids are a good match to the "round" production cone of laser accelerated particles; a quadrupole based focusing system appears to be disadvantageous in the defocusing plane of the first lens due to the relatively large production angles, hence we limit our study to a solenoid magnet. In order to estimate this effect for a specific parameter set we use the short pulsed solenoid currently under experimental study at GSI. It has a length of 72 mm and theoretical maximum field strength of 16 T sufficient to parallelize protons at 10 MeV (Figure 6.4). The distance target spot to solenoid edge is assumed to be 17 mm.

The prevailing higher order effect of a solenoid is the increase of the focal length with particle energy. Due to the de-bunching process different sections along the bunch have different energy and thus focus at different distances. This results in an effective increase of the bunch-averaged emittance to the effect that the tiny initial production emittance should be replaced by a *chromatic* emittance. In order to examine the expected behavior in detailed simulation we have employed the DYNAMION code [*9.7*], which includes higher order effects in amplitudes and energy dependence as well as space charge effects. The latter are based on particle-particle interaction, which limits the space charge resolution. The solenoid 3D magnetic field has been obtained by direct integration [*9.8*] using the coil geometry of the experimental solenoid. In order to quantify the chromatic effect we consider an ensemble of protons with constant energy spread $\Delta E/E = \pm 0.04$ around a reference energy of 10 MeV. Results for final emittances (ignoring space charge) are found in Figure 9.4 to depend exactly quadratically on the considered production cone opening angle $\delta x'$, which was varied up to ±172 mrad (±10°).

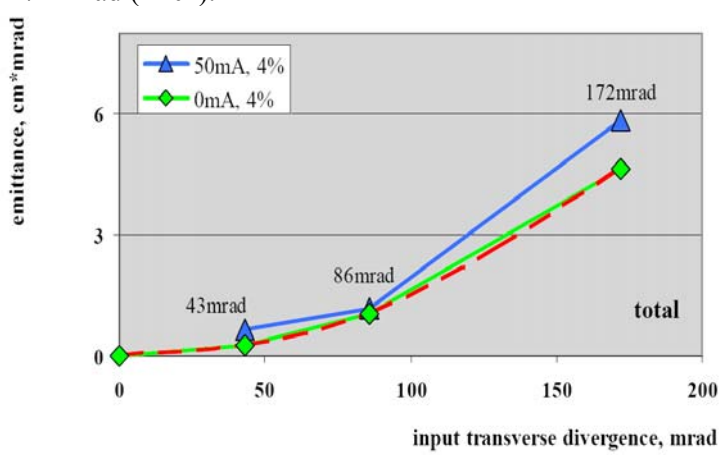


Figure 9.4: *Dependence of "chromatic" emittances (here total emittances for 95% of particles) on production cone angle as obtained by Dynamion simulations.*

To test the influence of space charge we also simulated a case with the number of N_b protons in the bunch equal to $3x10^9$, which is equivalent to a linac current of I=50 mA (using $I=eN_bf_{RF}$ and assuming that each bucket of a f_{RF}=108 MHz sequence is filled identically). For simplicity the bunch intensity was chosen independent of the opening angle. It is noted that the quadratic law still roughly applies.

Since for given δx' the dependence on ΔE/E is found practically linear, we can justify the following scaling of the chromatic emittances in the absence of space charge:

$$\varepsilon_x = \alpha_c (\delta x')^2 \frac{\Delta E}{E}$$

with α_c~0.04 m/rad for the particular solenoid described here [*9.9*]. The law is still roughly conserved if space charge is included for the assumed bunch intensity. Note that the chromatic emittance is found practically independent of the initial spot radius r_{spot} – contrary to the production emittance given by the product r_{spot} δx'.

Transmission through beam pipe

For the planned experiment it is important to note that the increase of emittance with energy spread will inevitably lead to transmission loss in the finite acceptance of the following beam pipe. To this end we have assumed a beam pipe of 3 cm radius up to 250 cm distance from the source. We have also assumed a linac current $N_b \sim \Delta E/E$, with $N_b=2x10^9$ for the lowest value ΔE/E= ±0.04. Typical results for the transmission assuming the initial cone opening angle δx' = ±172 mrad (±10^0) are given in Figure 9.5.

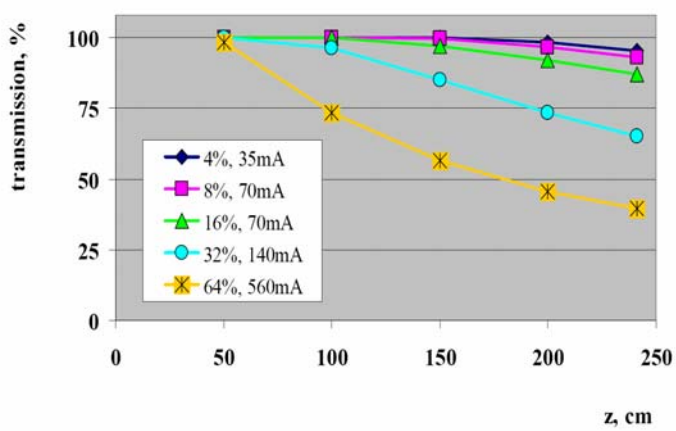


Figure 9.5: *Transmission through a beam pipe of radius 3 cm as function of distance from source (Dynamion simulation).*

The increasing transmission loss with distance is mostly due to the large spread of focusing angles as function of the energy spread, and to a lesser extent due to space charge. The surviving energy distribution evaluated at different distances from the source is shown in Fig. 9.6 for the largest initial energy spread case in Fig. 9.5 of ΔE/E= ±0.64 and correspondingly high current.
Obviously an extended beam pipe serves as energy filter. Further filtering down to smaller energy windows – limiting the transmission basically to ΔE/E= ±0.04 – is achieved by reducing the available aperture with a smaller radius diaphragm.

RF bunch rotation

For most applications of laser accelerated particles, in particular for ion beam therapy, it is desirable to reduce the final energy spread on target to a fraction of a per cent in

order to enable focusing on a small target spot. This is achieved by means of a "bunch rotation" RF cavity applied to the beam after de-bunching to a length suitable for the RF wavelength. The initial short bunch length increases with de-bunching proportional to the distance from the source and the considered energy spread. Capture into the RF bucket of a fraction of beam within a given transverse emittance defines the ultimate 6D extraction efficiency and the "usable" part of the total production of protons.

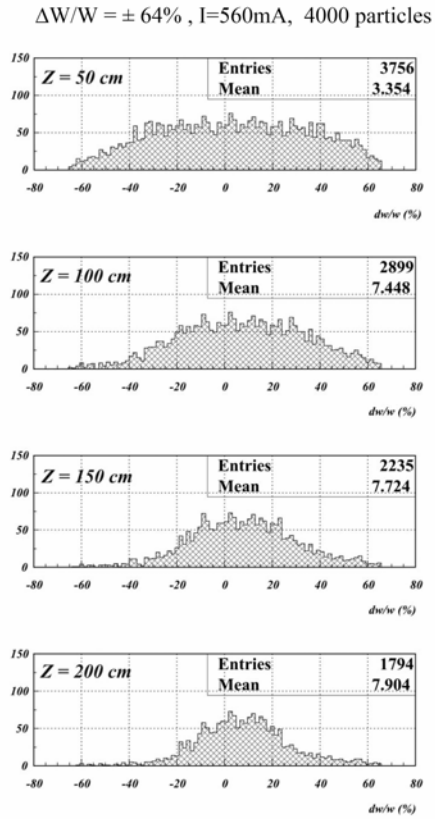


Figure 9.6: *Transmission energy spectrum for initial ΔE/E= ±0.64 as function of distance from source (Dynamion simulation).*

As reference value we take an energy spread of ΔE/E = ±0.04, which can be reduced to a reasonably small value by using a 500 kV / 108 MHz bunch rotation RF cavity approximately 250 cm away from the solenoid. This means that only the central part of the totally transmitted energy distribution – about 20% of it for the 3cm aperture limitation – can be captured by the RF bucket. Diagnosing the intensity and 6D emittance of this "usable" fraction in the presence of the background of the fully transmitted spectrum is a challenge to the diagnostics.

9.3) Matching the Laser Generated p-bunch into a CH-DTL

A high intensity proton beam produced by Target Normal Sheath Acceleration from thin foil could be used as an injector into a linac at injection energies of ten to several tens of MeV when compared to state of the art injectors. The important topic for a further acceleration of the laser generated bunch is the matching into the acceptance of an RF accelerator. Due to the available energies drift tube structures are the most adequate choice. A Cross Bar H-Type (CH-structure) is suggested as the linac

structure because of its high acceleration gradients, β- range, mechanical robustness, and high shunt impedance at the relevant energies.
The motivation for such a combination is to deliver single beam bunches with quite small emittance values at extremely high particle number per bunch. To compare with conventional beam currents the sum current of these bunches might add up to 500 mA beam current if every bucket would be filled with that ion number. This may be compared to 100 mA beam current which is state of the art in conventional injector techniques.

The Prototype-Cavity for the FAIR-Proton Linac

A CH-DTL cavity (Figure 9.7) is under construction at IAP Frankfurt [*9.10*, *9.11*].

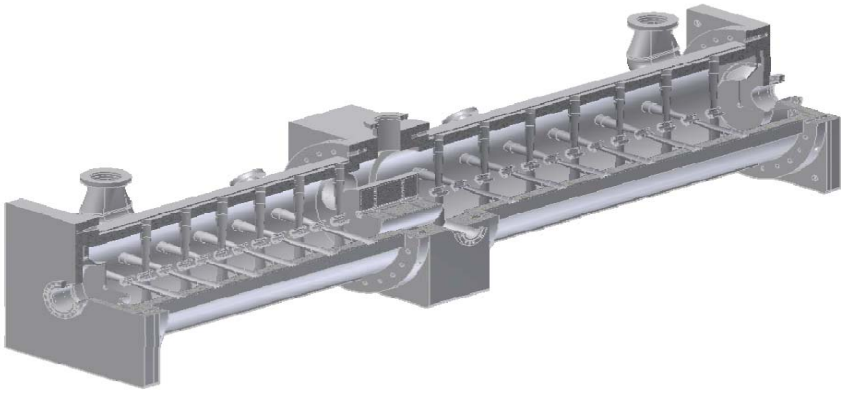


Figure 9.7: *The coupled CH-DTL*

The parameters are given in table 9.1. With respect to Laser accelerated beams the capability of that type of rf linac for high current beams has to be investigated.
Both longitudinal and transverse beam dynamics were studied. The envelopes resulting from 100.000 particles run with a water bag input distribution are shown in figure 9.8. The particle distributions at entrance and exit in transverse and longitudinal planes are shown in figure 9.9.

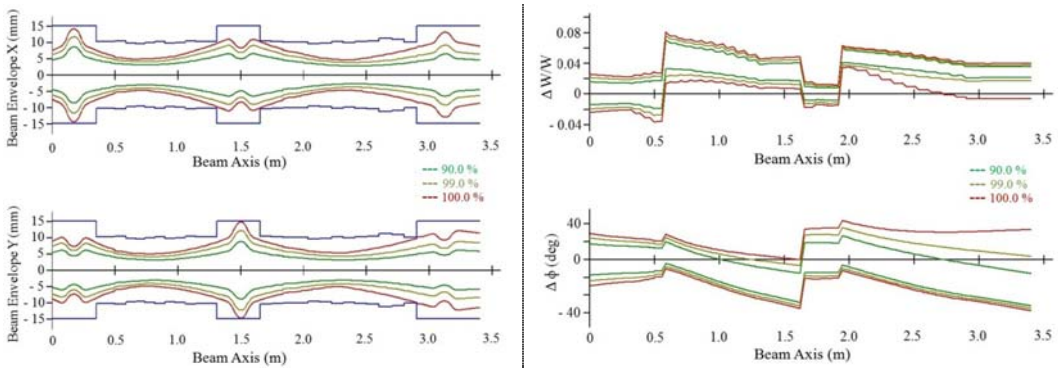


Figure 9.8: *Transverse (left) and longitudinal (right) envelopes at 500 mA beam current.*

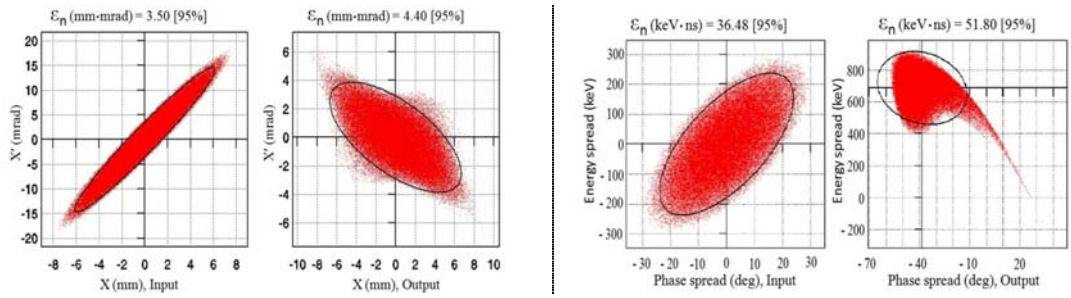


Figure 9.9: *Transverse (a) and longitudinal (b) particle distribution at entrance and exit of the CH-DTL section at 500 mA beam current.*

No. of Gaps	27
Frequency (MHz)	325.244
Energy Range (MeV)	11.7-24.3
Beam Loading (kW)	882.6
Heat Loss (MW)	1.35
Total Power (MW)	2.2
Q_0-Value	15300
Effective Shunt Impedance (MΩ/m)	60
Average E_0T (MV/m)	5.8 – 6.4
Kilpatrick Factor	2.0
Coupling Constant (%)	0.3
No. of Plungers	11
Beam Aperture (mm)	20
Total Length (mm)	3000

Table 9.1: *The main parameters of a coupled CH-DTL*

Table 9.2 summarizes matched emittance values for longitudinal and transversal planes for 500 mA. These beam intensities are better than state of the art at high current linacs. The emittance growth along the cavity was less than 45% in longitudinal plane and about 20% in transverse planes.

Beam Current	Beam Parmeters	Input	Output
500 mA	ε_{tr}	0.69	0.84 mm-mrad
	ε_{long}	7.25	10.42 keV-ns

Table 9.2: *Emittance values for the input and output distribution.*

The injection energy of this cavity is well matched to the proton energy spectrum that was generated by PHELIX. So it seems that this cavity is well suited for the first injection test of a laser generated p- beam into an rf linac.

Matching into the CH-DTL by a Solenoid

The possibility of injecting the proton beam which is generated by laser was investigated and a new design of CH-DTL was suggested at the IAP- Frankfurt. The magnetic solenoid which is used for focusing the beam was studied as a part of this design.

This design is also operated at 325.244 MHz and is starting with a magnetic solenoid. The DTL consists of 9 gaps (4 gaps for reb. and 5 gaps for acc.) within 1.22 m total length. It accelerates the protons from 10.03 MeV to 17.37 MeV (acceleration gradient = 11.89 MeV/m) [*9.12*, *9.13*]. The beam parameters are summarized in table 9.3.

Beam Current	Beam Parmeters	Input	Output
500 mA	ε_{tr}	0.33	0.53 mm-mrad
	ε_{long}	3.22	4.08 keV-ns

Table 9.3: *Emittance values for the input and output distribution.*

The emittance growth is less than 30% for longitudinal plane and about 65% for the transverse planes as shown in figure 9.10. The beam dynamics was done by LORASR code for longitudinal and transverse motion. The emittance results are still within accepted ranges.

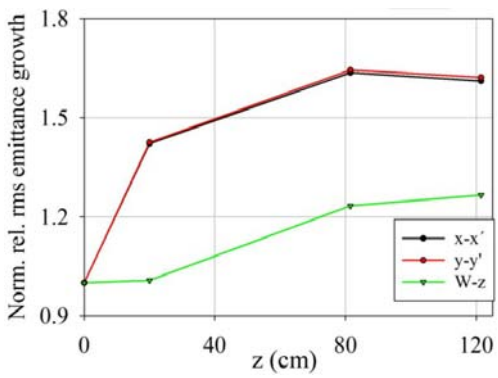


Figure 9.10: *Emittance growth through the design*

The envelopes resulting from 100.000 particle runs can be seen in figure 9.11. The magnetic field gradients of the quadrupoles are ranging up to 65 T/m and up to 18 T for the 72 mm solenoid.

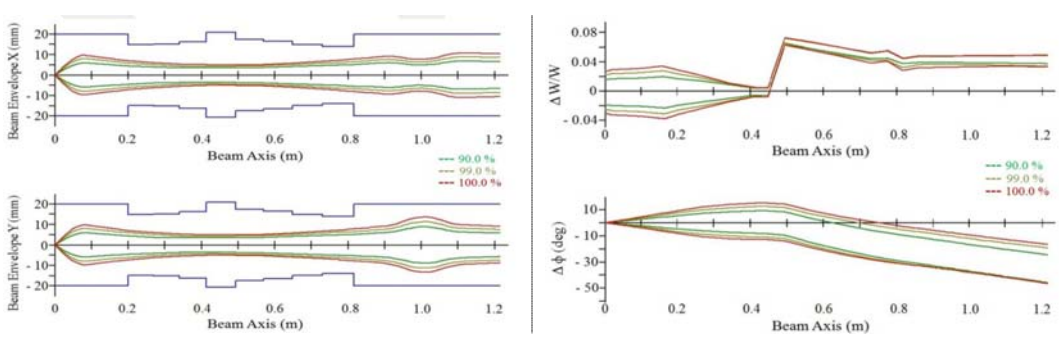


Figure 9.11: *Transverse (left) and Longitudinal (right) envelopes*

The particle distribution at entrance and exit in transverse and longitudinal planes are shown in figure 9.12.

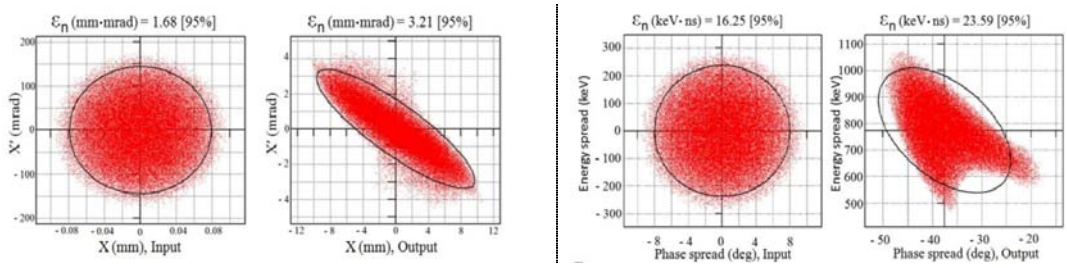


Figure 9.12: *Transverse (a) and longitudinal (b) particle distribution at entrance of solenoid and exit of the CH-DTL section.*

Emittances behind the foil and their indirect measurement behind a tank cavity

The proton beam that is generated by the laser might have a length of 500 fs (about 0.06 degree spread in phase space). The longitudinal and transverse emittance is quite small ($\varepsilon_{long.}$ = 0.0193 keV-ns and $\varepsilon_{tr.}$ = 0.0990 mm-mrad) originally. For such small emittance beams, we will face a problem in the emittance growth through the solenoid and the CH-structure especially in longitudinal plane which may show factors of 100 and more (Figure 9.13). To reduce this growth, it is better to increase the length of the proton pulse in order to increase the phase spread which is limited by the laser pulse. It means that one main task of this project will be to find matching tools between laser driven spot at the starting point and injection into the cavity which not only shape the emittance areas but also give them reasonable absolute numbers. Let's call it a well controlled emittance growth process. One way towards better matching of absolute numbers would be a significant increase in beam energy from the laser injector.

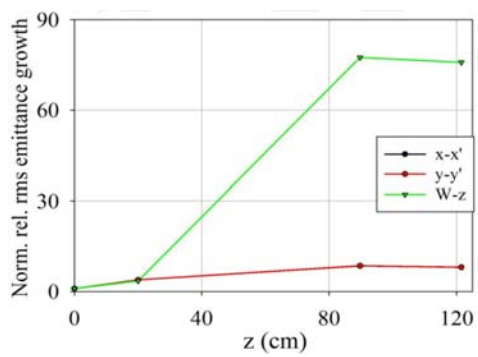


Figure 9.13: *Emittance growth through the design longitudinal and Transverse.*

The particle distribution at entrance and exit in transverse and longitudinal planes are shown in figure 9.14, here one can see the effect of small emittances on the particle distribution especially on longitudinal plane.

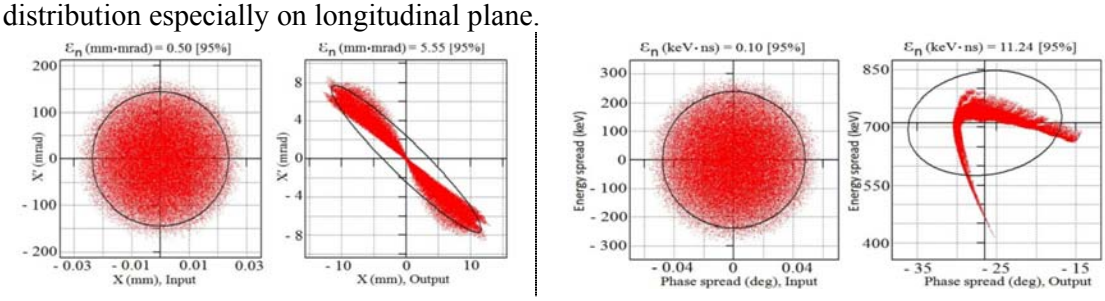


Figure 9.14: *Transverse (a) and longitudinal (b) particle distribution at entrance of solenoid and exit of the CH-DTL section.*

9. Appendix

Due to well known transformations of the injected beam emittances along the CH-cavity, it is aimed to derive the TNSA generated emittances by measuring the beam properties behind of the CH- cavity. Different CH operation settings should allow to solve this interesting task.

References

[*9.1*] *S. Pfotenhauer et al., "A cascaded laser acceleration scheme for the generation of spectrally controlled proton beams", submitted to New Journal of Physics (2009)*

[*9.2*] *A. Henig et al., "Enhanced Laser-Driven Ion Acceleration in the Relativistic Transparency Regime", Physical Review Letters (2009)*

[*9.3*] *A. Robinson et al., "Radiation Pressure Acceleration of thin foils with circularly polarized laser pulses", New Journal of Physics (2008)*

[*9.4*] *A. Henig et al., "Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses", Physical Review Letters (2009)*

[*9.5*] *H. Schwoerer et al., "Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets", Nature (2006)*

[*9.6*] *S. ter-Avetisyan et al., "Quasimonoenergetic Deuteron Bursts Produced by Ultraintense Laser Pulses", Physical Review Letters (2006)*

[*9.7*] *S. Yaramishev et al. Nucl. Instr. Meth., A 558, 1 (2006)*

[*9.8*] *M. Droba, private communication*

[*9.9*] *I. Hofmann et al., "Laser accelerated ions and their potential for therapy accelerators", Proc. HIAT09, Venice, June 6-12, 2009*

[*9.10*] *R. Brodhage et. al., "Prototype Construction of a Coupled CH-DTL Proton LINAC for FAIR", Proc. PAC 09, Vancouver, BC, Canada (2009).*

[*9.11*] *R. Brodhage et. al., "Development and Measurements on a Coupled CH Proton LINAC for FAIR", Proc. IPAC 10, Kyoto, Japan (2010).*

[*9.12*] *A. Almomani et. al., "Matching the Laser Generated P-Bunch into a CH-DTL", Proc. IPAC 10, Kyoto, Japan (2010).*

[*9.13*] *A. Almomani et. al., "Matching the laser generated p- bunch into a CH-DTL", GSI Scientific Report p. 407 (2009).*