H^- BEAM OPTICS FOR THE LASER STRIPPING PROJECT

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Abstract

Successful realization of the laser stripping experiment depends on the correct tailoring of the H^- bunch and the laser beam. H^- beam preparation is a challenging task, with the requirement to tune up about 10 parameters simultaneously in situ, taking into account the live state of the accelerator. This makes a huge technological difference compared to the foil stripping method. In this paper, we present our experience and our methods of tuning the H^- beam.

INTRODUCTION

We prepared an experiment to demonstrate laser assisted stripping of a 10 microsecond H^- beam at the Spallation Neutron Source (SNS) accelerator. The general up-to-date information about the status of the project can be found in [1, 2]. More information about the history and background can be found in [3, 4]. The new experiment expects to achieve more than 90% stripping efficiency. This requires an experimental station including routine hardware, magnets [5], and beam instrumentation. The most important scientific aspect for successful realization of the experiment is the tuning of the laser beam and the H^- beam at the interaction point. The recent work about the laser system can be found in [6]. In this present paper, we present a theory and experimental methods of tuning the H^- beam.

The first big challenge of beam tuning is that all of the H^- beam parameters, such as Twiss parameters and the dispersion functions, must be tuned simultaneously for high efficiency stripping. Laser tuning is a large, separate work and is based on the H^- beam parameters. This factor makes the method of laser stripping injection much more difficult compared to the foil stripping injection. Another particular difficulty is that the SNS accelerator has not been developed for this sort of experiment, and beam tuning and manipulation is limited and not optimized. The location of the experiment has been chosen taking into account maximum beam flexibility at the interaction point (Figure 1).

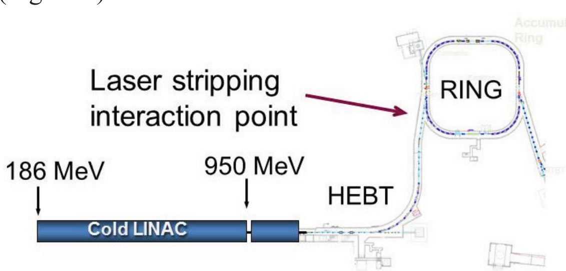

Figure 1. Location of the laser stripping experiment at SNS.

In this paper we will discuss various methods of H- beam parameter tuning for the laser stripping experiment.

INTERACTION BETWEEN H^0 AND LASER BEAM

After $H^- \rightarrow H^0 + e^-$ stripping by the first stripping magnet, the H^0 bunch interacts with the laser beam at the interaction point (Figure 2), which provides excitation of

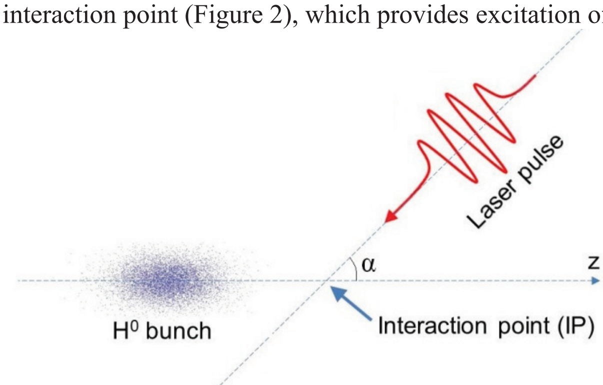

Figure 2. Interaction of H^0 beam with the laser beam.

H^0 from the first ground state to the third excited state. The beam energy is supposed to be 1 GeV in the experiment and incidence angle α between laser and H^0 beam, which can be calculated from Equation (1) [3]:

$$\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)} \quad (1)$$

where γ and β are relativistic factors of a bunch. This formula gives most optimal resonant conditions for H^0 beam excitation. This formula gives $\alpha = 39.33^0$ for $T_{H0} =$ 1 GeV. The theory of laser stripping excitation [3] shows that each particle of the H^0 beam should interact with the laser beam in a proper way (it must have proper energy, angle, and position). In this way, Twiss parameters of the H^0 bunch must be properly tuned for high efficiency excitation.

TRANSVERSE BEAM OPTICS

Transverse beam parameters can be defined at least by three vertical $\{\alpha_y, \beta_y, \varepsilon_y\}$, and three horizontal $\{\alpha_x, \beta_x, \varepsilon_x\}$ Twiss parameters plus dispersion and its derivative. The laser stripping location point (see Figure 1) has a large number of "knobs" to control these parameters.

Transverse Emittances

Equation (1) can be considered as a perfect resonant condition for particle excitation, although the whole bunch has some angular spread depending on emittances ε_x, ε_y. The default non-normalized emittances during SNS production is about 0.3 π mm × mrad for the vertical and the horizontal plane. This number can be reduced to 0.1 π mm × mrad and smaller with the help of LINAC apertures. In addition to the angular spread, small

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transverse emittances allow the achievement of a small transverse size that improves the overlap between the small laser beam and the H^0 beam.

Tuning of Transverse Twiss Parameters

The SNS accelerator has a large number of quadrupoles to manipulate the beam at the interaction point. There is a big question that has been studied empirically: what should be the optimal number of quadruples upstream of the interaction point? On one hand, a small number of quadrupoles gives limited flexibility to manipulate the beam. On the other hand, a large number of quadrupoles provide better flexibility to control beam parameters but involve a very long part of the accelerator and make it difficult to provide a good agreement with a model. After some empirical study, we decided to take last 7 upstream quadrupoles Quad20–Quad26 for tuning the transverse beam parameters. The method follows these three stages:

1) We measure more than three vertical and horizontal beam profiles to determine Twiss parameters at the beginning of Quad20.
2) We run an application that optimizes Twiss parameters at the interaction point and generates a number of Quad20–Quad26 solutions (Figure 3).
3) We select the most optimal solution with the best combination of H^0 bunch parameters.

The application defines goals parameters at the interaction point and gives multiple solutions for this interaction point. Then we set up quadrupoles for the selected solution from the table. Different Twiss parameters have a different role at the interaction point.

Vertical and Horizontal Size

As a rule, the laser beam has a small transverse size and a large power density. For this reason, the vertical size of the H^0 beam should be small enough to provide good overlap with the laser beam. Solutions in Figure 3 show that we can tune the beam with vertical root-mean-square (rms) size < 0.1 mm. Figure 4 shows that the predicted vertical size agrees with the measurement.

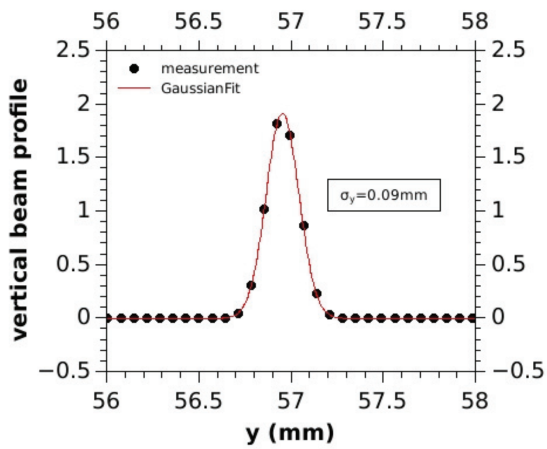
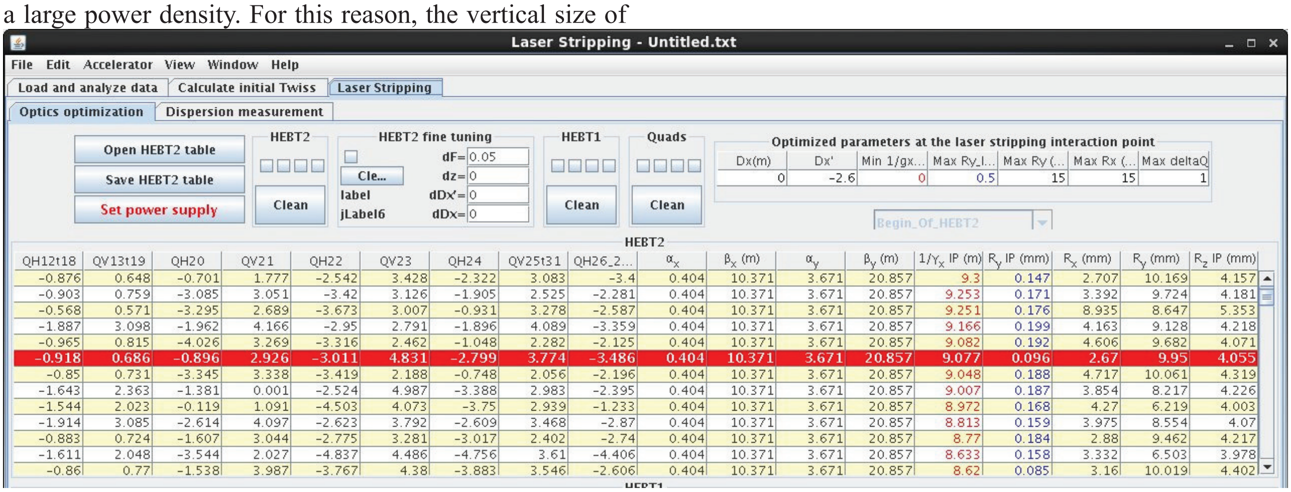


Figure 4. Example of vertical beam profile measured with the wire scanner for one of beam tuning.

The final vertical size is an important parameter to know prior to the experiment because it defines the laser beam size to be adjusted. The horizontal size is not as important as the vertical size because the laser shoots in a horizontal plane. However, the horizontal transverse size is still important and should be smaller than about 2 mm. The horizontal beam size also correlates with the horizontal angular spread, which is much more important (see the "Horizontal angular spread" section below).



QH12t18	QV13t19	QH20	QV21	QH22	QV23	QH24	QV25t31	QH26_2...	α_x	β_x (m)	α_y	β_y (m)	$1/\gamma_x$ IP (m)	R_y IP (mm)	R_x (mm)	R_y (mm)	R_z IP (mm)
-0.876	0.648	-0.701	1.777	-2.542	3.428	-2.322	3.083	-3.4	0.404	10.371	3.671	20.857	9.3	0.147	2.707	10.169	4.157
-0.903	0.759	-3.085	3.051	-3.42	3.126	-1.905	2.525	-2.281	0.404	10.371	3.671	20.857	9.253	0.171	3.392	9.724	4.181
-0.568	0.571	-3.295	2.689	-3.673	3.007	-0.931	3.278	-2.587	0.404	10.371	3.671	20.857	9.251	0.176	8.935	8.647	5.353
-1.887	3.098	-1.962	4.166	-2.95	2.791	-1.896	4.089	-3.359	0.404	10.371	3.671	20.857	9.166	0.199	4.163	9.128	4.218
-0.965	0.815	-4.026	3.269	-3.316	2.462	-1.048	2.282	-2.125	0.404	10.371	3.671	20.857	9.082	0.192	4.606	9.682	4.071
-0.918	0.686	-0.896	2.926	-3.011	4.831	-2.799	3.774	-3.486	0.404	10.371	3.671	20.857	9.077	0.096	2.67	9.95	4.055
-0.85	0.731	-3.345	3.338	-3.419	2.188	-0.748	2.056	-2.196	0.404	10.371	3.671	20.857	9.048	0.188	4.717	10.061	4.319
-1.643	2.363	-1.381	0.001	-2.524	4.987	-3.388	2.983	-2.395	0.404	10.371	3.671	20.857	9.007	0.187	3.854	8.217	4.226
-1.544	2.023	-0.119	1.091	-4.503	4.073	-3.75	2.939	-1.233	0.404	10.371	3.671	20.857	8.972	0.168	4.27	6.219	4.003
-1.914	3.085	-2.614	4.097	-2.623	3.792	-2.609	3.468	-2.87	0.404	10.371	3.671	20.857	8.813	0.159	3.975	8.554	4.07
-0.883	0.724	-1.607	3.044	-2.775	3.281	-3.017	2.402	-2.74	0.404	10.371	3.671	20.857	8.77	0.184	2.88	9.462	4.217
-1.611	2.048	-3.544	2.027	-4.837	4.486	-4.756	3.61	-4.406	0.404	10.371	3.671	20.857	8.633	0.158	3.332	6.503	3.978
-0.86	0.77	-1.538	3.987	-3.767	4.38	-3.883	3.546	-2.606	0.404	10.371	3.671	20.857	8.62	0.085	3.16	10.019	4.402

Figure 3. Screenshort of the application with an example of generated solutions for laser stripping.

Maximum Beam Size

The "R_x" and "R_y" columns in Figure 3 show the maximum transverse beam size along the Quad20–Quad26 that should be small enough (less than 10 mm) to prevent beam losses in a vacuum chamber.

Horizontal Angular Spread

The horizontal angular beam spread is considered to be one of the main impacts for resonant excitation (1) and it should be as small as possible for more excitation efficiency. In a simple model, the rms angular spread is proportional to Twiss parameter $\gamma^{1/2}$ where $\gamma = (1 + \alpha^2)/\beta$.

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In this way 1/γ should be as big as possible (see the corresponding column in Figure 3). A bigger value of 1/γ leads to a bigger horizontal beam size and produces a worse result. The empirical study shows that the optimal value should be about 10.

Horizontal Dispersion Function

Bending magnets of SNS accelerator (see Figure 1) give extra flexibility to manipulate the horizontal dispersion function at the interaction point, which would be zero in pure LINAC configuration. Horizontal beam size depends on D_x function that must be zero at the interaction point to keep the horizontal size smaller.

Horizontal Dispersion Derivative Function

This is probably the most interesting parameter from the point of view of laser stripping theory. Equation (1) gives the perfect resonant condition incidence angle-energy relation for the H^0 particle. The laser cannot be adjusted perfectly for all beam particles because of its angular-energy spread, but the resonant condition can be significantly improved by introducing correlation according to (1) between angle-energy for particles in the bunch. The parameter of dispersion derivative D_x' is responsible for the correlation and it can be adjusted due to the SNS dipole bending magnets. Optimal D_x' can be calculated from the following equation:

$$D_x' = \frac{\dfrac{\lambda}{\lambda_0} - \dfrac{m}{m+T}}{\sqrt{2\dfrac{\lambda}{\lambda_0}\dfrac{T}{m} - \left(\dfrac{\lambda}{\lambda_0} - 1\right)^2}} . \tag{2}$$

$D_x' = 2.6$ for $T = 1$ GeV H^0 beam energy, $\lambda_0 = 102.5$ nm, $\lambda = 355$ nm, $m_{H0} = 0.938$ GeV (mass of H^0). D_x is defined as $-\Delta x/(\Delta p_z/p_z)$. The sign of D_x' is important and depends on the frame and the laser beam direction. It should be -2.6 in our definitions.

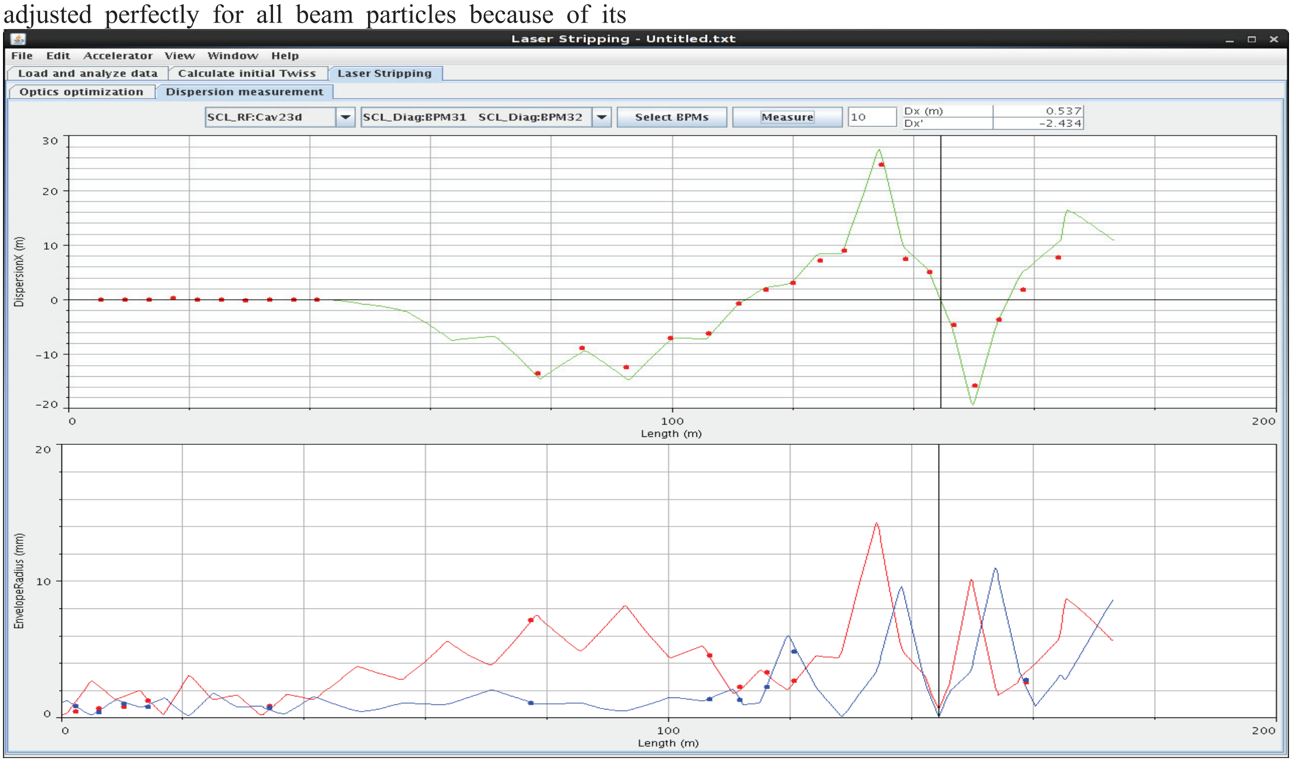

Figure 5. Laser stripping experimental tuning of transverse parameters for laser stripping.

Experimental Tuning of Transverse Beam Parameters

Figure 5 presents an example of tuning transverse parameters for laser stripping at the interaction point. The lower picture presents the vertical and horizontal size of the beam (solid lines for a model and a point for experimental measurements with the help of a wire scanner). The upper plot shows the dispersion function. It can be seen that the model agrees with the experimental measurements—at least at the vicinity of the interaction point—five wirescanners to the left and one wirescanner from the right. The laser stripping parameters at the interaction point can be measured after wire scanner installation for the experiment.

Fine Tuning of Transverse Beam Parameters

The parameters, r_x, r_y, D_x, D_x', measured at the interaction point, can be different from the model; for example, $D_x = 0.5$ m instead of 0.0 m and $D_x' = -2.43$ instead of -2.6 (see Figure 5). The application (Figure 3) has an option for a small correction of the parameters. After a satisfied solution has been chosen and the parameters at the interaction point have been measured, this function changes the parameters for a small value without changing other ones. In this way, there is a chance to correct the parameters for better efficiency.

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LONGITUDINAL BEAM OPTICS

The laser beam has micropulse duration of 55 ps FWHM [6]. In this way, it is obvious that the H^0 micropulse should be comparable to the laser pulse for good overlap. Calculations [7] show that the longitudinal rms size of the H^0 should be 3 degrees (25ps FWHM) or smaller in terms of 805 MHz frequency. Measurements of the default beam at the interaction point gives 10–20 degrees (see Figure 6).

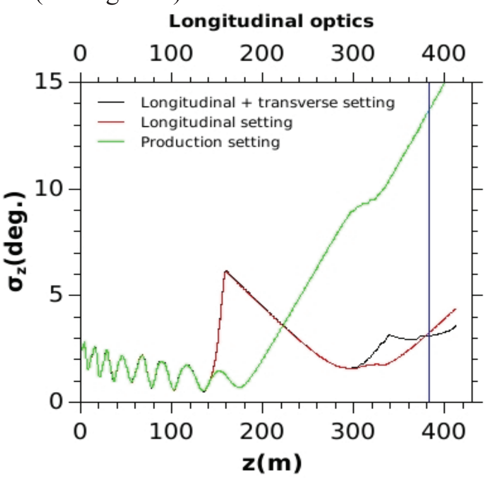

Figure 6. Longitudinal beam size for different cavity settings.

Previous work [7] presents a detailed theoretical and experimental study of the bunch shortening. In this paper, Figure 6 shows that a shortened bunch between 300 m and 380 m has an extraordinary significant jump in bending magnets when the quadrupoles are adjusted for transverse laser stripping tuning. The last column of the table in Figure 3 presents the approximate longitudinal beam size, which is important when selecting the optimal solution for laser stripping. Calculations show that it's acceptable to have solution with 4 degrees maximum longitudinal size. Figure 7 presents the space charge effect on the longitudinal beam size.

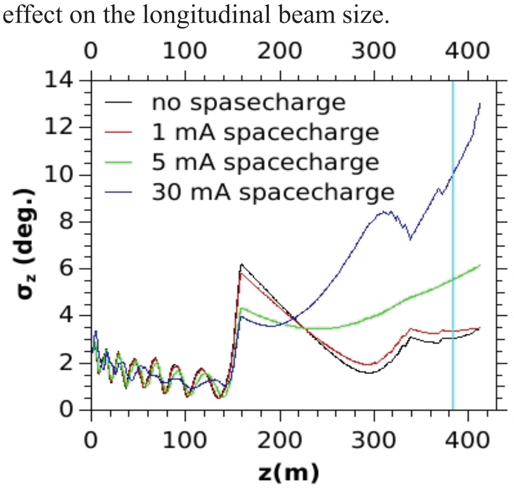

Figure 7. Space charge effect.

The average current of H^- minipulse should not exceed 1 mA for the laser stripping experiment.

LASER STRIPPING EFFICIENCY

The laser stripping efficiency calculation must be based upon bunch parameters achieved in an experiment. At this time, independent transverse and longitudinal beam parameters have been achieved separately and can be used to generate a realistic beam for an efficiency estimate. We do it in the following way: The laser stripping application in Figure 3 has been developed for online beam tuning. It is based on a linear envelope model and is written for a fast solution of the bunch optimization.

1) We take parameters of quadrupole fields and input emittance and insert them into the PyOrbit [8] accelerator program together with the longitudinal bunch shortening cavity configuration.
2) After tracking the particle beam, we obtain the H^0 particle bunch at the laser stripping interaction point.
3) We use the H^0 bunch for the laser stripping application also written in the PyOrbit code to calculate laser stripping efficiency.

We used 10,000 particles for H^0 bunch simulations. The example of longitudinal phase space distribution is shown in Figure 8.

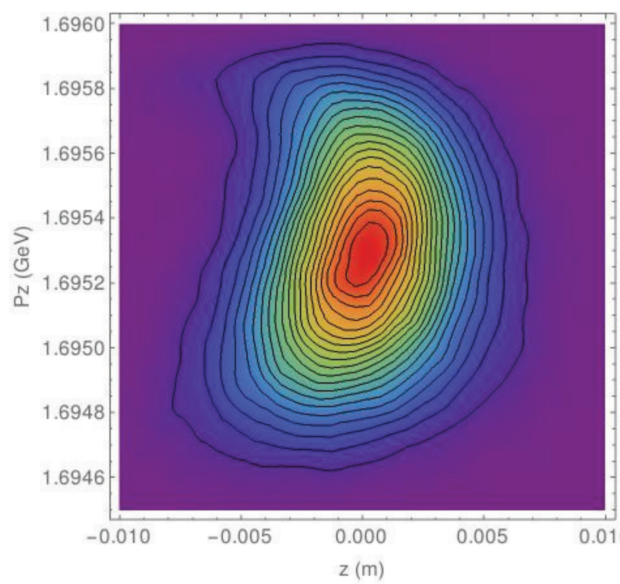

Figure 8. Longitudinal phase space of H^0 bunch at the interaction point generated by the PyOrbit code.

Figure 8 clearly demonstrates non-Gaussian behavior of the bunch. We used the round Gaussian laser beam for simulations (Figure 9).

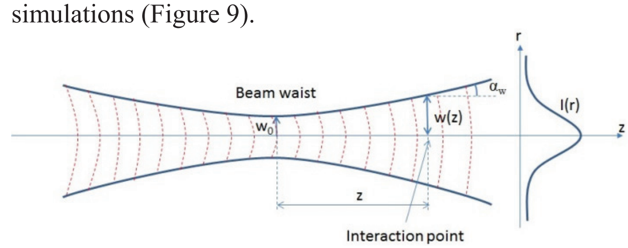

Figure 9. The round Gaussian laser beam for laser stripping simulations.

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The laser beam is defined by fixed parameters of Peak power = 0.8 MW, and longitudinal pulse width FWHM = 55 ps. The variable laser beam parameters at the excitation point w and α_w = dw/dz is replaced by the beam radius of power density r = 0.5 w and the radius slope α_r = 0.5 α_w. Figure 10 presents laser stripping efficiency as a function of r and α_r.

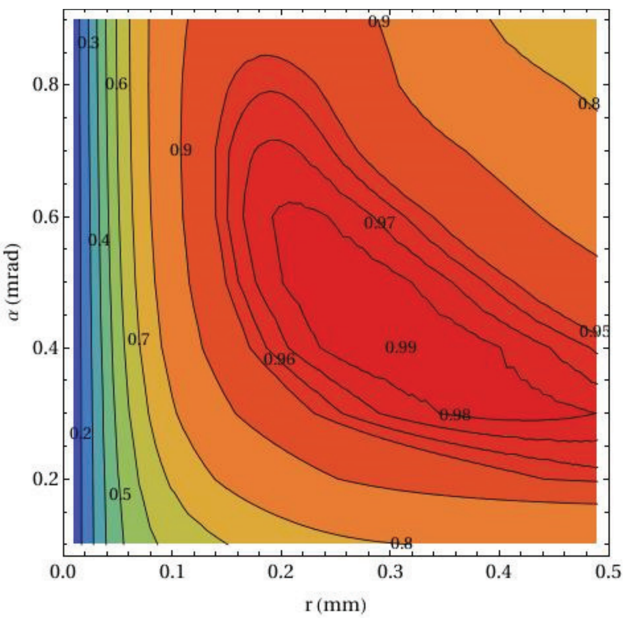

Figure 10. Laser stripping efficiency as a function of the variable laser beam parameters of the radius and its divergence.

The peak of this plot has a single point with 99% of excitation efficiency for r ≈ 0.3mm and α_r ≈ 0.4 mrad. This picture is important for the design of a laser system because tuning a laser beam optics is not as flexible as an H^- beam optics and must be known in advance. It should be noted that this is just up-to-date study of laser stripping efficiency; final calculations can be done only after diagnostics are installed at the interaction point and after the final beam tuning is done for 1 GeV beam.

Figure 9 schematically represents interaction point z and beam divergence α with a positive sign while the real experimental interaction point will have a negative sign and convergence for technical simplicity. Figure 10 has symmetry relatively to beam divergence α.

SUMMARY

- Transverse and longitudinal tuning of the H^- beam has been studied separately and satisfactory beam parameters have been achieved.
- As a next step, it would be good to make simultaneous experimental tuning of transverse and longitudinal beam parameters.
- A lot of empirical methods and parameter tuning have been learned during the study of H^0 beam optics in spite of the existing straightforward models of beam dynamics.
- An application for online laser stripping H^- beam tuning has been developed. Real beam tuning functions, such as a beam correction, have been implemented into the application.
- Calculations show that a bunch with the achieved longitudinal and transverse parameters would give 99% laser stripping efficiency.

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