ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPRB116

LASER SCULPTED COOL PROTON BEAMS

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Abstract

Hydrogen ion accelerators, such as CERN's LINAC4, are increasingly used as the front end of high power proton drivers for high energy physics, spallation neutron sources and other applications. Typically, a foil strips the hydrogen ion beam to facilitate charge-exchange injection of protons into orbits of high energy accelerators, in which the resulting emittance is dominated by phase-space painting. In this paper, a new method to laser extract a narrow beam of neutralised hydrogen from the parent H^- ion beam is proposed. Subsequent foil stripping and capture of protons into a storage ring generates cool proton bunches with significantly reduced emittance compared to the parent beam. The properties of the extracted proton beam can be precisely controlled and sculpted by adjusting the optical parameters of the laser beam. Recirculation of the parent beam allows time for space-charge effects to repopulate the emittance phase space prior to repeated laser extraction. We present particle tracking simulations of the proposed scheme, including the laser-particle interaction with realistic optical parameters and show the resulting emittance is reduced. Developments for an experimental demonstration of a laser controlled particle beam are outlined. In principle, the proposed scheme could considerably reduce the emittance of protons bunches injected into an accelerator, such as the LHC.

INTRODUCTION

State-of-the-art proton accelerators for high energy physics, spallation neutron sources and other applications are increasingly driven by high power hydrogen ion linacs. For example, in order to achieve the beam emittance requirements for the High Luminosity LHC, CERN's 50 MeV proton LINAC2 has been replaced since late 2018 by LINAC4; a 160 MeV H^- accelerator that will be the primary source in the injection chain from LHC Run-III. The use of hydrogen ions facilitates charge-exchange injection of protons at a stripping foil in the orbit bump of the first synchrotron booster [1,2]. A low emittance primary hydrogen beam is critical for efficient phase-space painting, which can dominate the emittance of the proton beam accumulated in the storage ring for subsequent acceleration. Due to the inherent emittance of the H^- ion source, methods to further reduce the beam emittance for high beam powers are desired.

In this paper, a new concept to generate an emittance cooled proton beam is proposed, starting from the laser controlled extraction of a narrow, neutralised H^0 beam from a larger, parent H^- beam. The intermediate H^0 beam then drifts to a stripping foil that removes the ground state electron and low emittance protons are captured in the storage ring for subsequent acceleration. The key advantage is that transverse size, position and angular divergence of the generated H^0 beam is determined by the laser parameters and overlap geometry and so very low emittance H^0 beams can be created. Thus cool proton beams can be precisely controlled and sculpted by adjusting the optical parameters and interaction geometry of the laser.

Note that this method is distinct from laser assisted stripping, whereby both electrons of the H^- ion are stripped, first using Lorentz stripping to H^0, then a high-power, short wavelength laser is required to excite the strongly bound ground state electron by optical nutation prior to stripping by field dissociation [3–7]. In the method proposed here, only the outer, loosely bound (0.75 eV) electron is photodetached by a highly focussed laser over a long interaction length, thus only a long wavelength (1064 nm), low power, fibre-coupled laser is needed, considerably simplifying the setup.

In the next section the basic concept of the laser sculpting interaction geometry is introduced. Secondly, simulations of realistic accelerator distributions of a single bunch passing once through the laser sculptor are presented. Finally the design of a multi-turn racetrack accelerator incorporating a laser-sculptor is simulated to demonstrate the principle of emittance reduction for a full beam.

LASER SCULPTED BEAMS CONCEPT

Optical methods for non-invasive diagnostics of hydrogen ion beams have been developed in recent years, for example at SNS [8–10], CERN's LINAC4 [11–18] and FETS [19–22]. Such systems essentially exploit a narrow laserwire *orthogonally incident* on the particle beam to photo-detach a small fraction of ions for monitoring purposes. Here, we propose to inject the laser beam *antiparallel* to the ion beam to enable the controlled generation and sculpting of an H^0 beam. The conceptual layout of the laser-ion beam interaction region is shown in Fig. 1, as modelled in BDSIM [23,24].

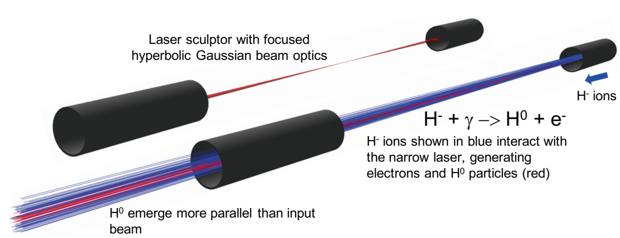

Figure 1: A *laser sculptor* modelled in BDSIM shows the simulated interaction between a narrow laser beam traversed by a larger H^- ion beam. Neutralised ions are sculpted from the core of the H^- beam producing an H^0 beam with reduced emittance defined by the geometrical overlap with the laser.

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When the narrow laser beam passes through the larger, high emittance ion beam, only H^- ions at its core overlap with the laser focus and are neutralised by photodetachment generating H^0 and electrons. Thus due to the geometry, a narrow H^0 beam is emitted very parallel to the laser. Low energy electrons can be captured by a Faraday cup for monitoring, while the unstripped H^- ions are deflected by a downstream dipole for recirculation in the racetrack storage ring, as described below. The H^0 distribution obtained depends [24] on the hyperbolic focus of the laser waist, the Rayleigh range, the relativistic Doppler-shifted wavelength, and on the initial Twiss parameters of the particle beam.

SINGLE BUNCH LASER SCULPTING

Simulation Model

The passage of an H^- ion bunch through a laser sculptor was simulated in an extension of BDSIM for Gaussian laser beams [23,24]. The aim was to calculate the fraction of ions that can be sculpted from the bunch in a single pass and to check that the emittance is reduced. Stripping efficiencies were investigated for three input bunch distributions:

H^- reference An ideal beam of H^- ions, with 160 MeV kinetic energy, central on the laser axis.

LINAC4 Low emittance, 160 MeV H^- ions from particle tracking simulations of CERN's LINAC4. [17]

FETS High emittance (ϵ_x, ϵ_y = 5.9, 5.6 mm mrad) 3 MeV H^- from parametrised GPT simulations of FETS. [22]

The laser sculptor was modelled as a focussed Gaussian beam, in which the peak flux is derived from the pulse energy and duration thus $\rho(x, y, z)$, the photon flux divided by the photon energy, anywhere in the laserwire is known. As an H^- ion traverses the laser beam the interaction probability is $P_s = 1 - e^{-\sigma(\lambda)\rho(x,y,z)t}$, where σ is the ion rest frame interaction cross-section in terms of the Doppler-shifted wavelength λ, and t is the integration time. The simulated laser parameters in Table 1 match those of a commercial fibre-laser previously demonstrated for H^- laserwires at LINAC4 [11–18].

Table 1: Laser Beam Parameters

Pulse energy	E_l	= 67.4 µJ
Pulse duration	P_l	= 106 ns
Wavelength	λ	= 1064 nm
Gaussian beam waist	w_0	= 100 µm
Laser beam quality	M^2	= 1.8
Rayleigh range	z_R	= 16.4 mm

Examples of Single Pass Bunch Sculpting

The response of H^- ions passing through the laser sculptor and the size of H^0 beam extracted is shown in Figs. 2 and 3 for the LINAC4 and FETS beams respectively. In both cases, the laser sculptor effectively drills a hole in the xy distributions of the H^- ions, and the extracted H^0 beam is clearly reduced in size and emittance compared to the input. Similar reductions are obtained in x′ vs x phase space. In both cases,

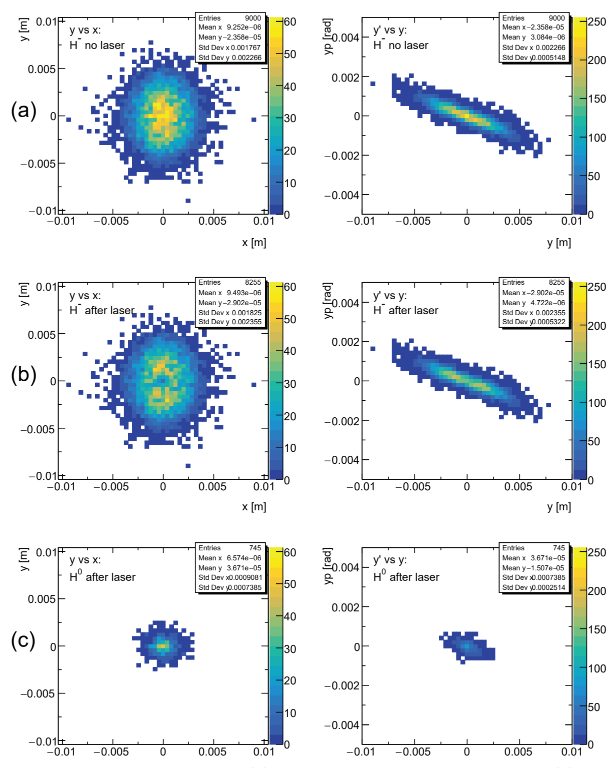

Figure 2: 160 MeV LINAC4 H^- beam: (a) no laser, (b) with laser and (c) the H^0 extracted by single pass laser sculpting.

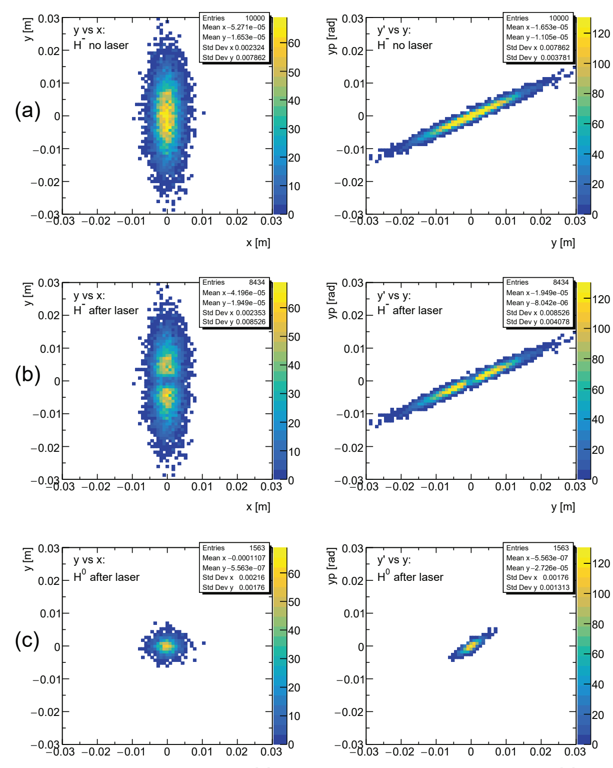

Figure 3: 3 MeV FETS H^- beam: (a) no laser, (b) with laser and (c) the H^0 extracted after single pass laser sculpting.

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the interaction probability was scaled by 100 for visualisation in the plot, giving stripping efficiencies of 100 % for the reference beam, 8.28 % for LINAC4 and 15.6 % for FETS. The effect of the scale factor on the stripping efficiency was investigated as in Fig. 4. For a scale factor of 1 and pulse en-

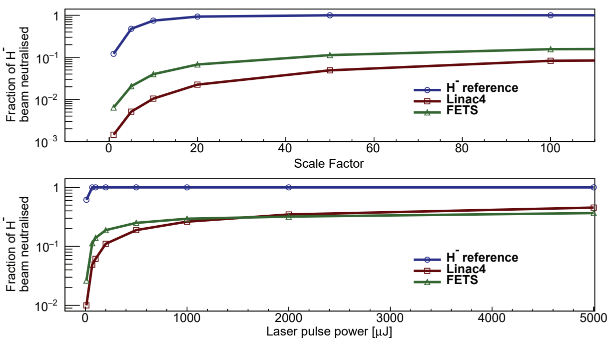

Figure 4: H^- single pass stripping efficiency through a 1 m long, w_0 = 0.1 mm laser sculptor as the interaction probability scale factor and laser pulse power are varied.

ergy of 67.4 µJ, a stripping efficiency above 10 % is achieved for the on-axis reference beam. The stripping efficiency rises rapidly with increased laser pulse power as in Fig. 4, and ultimately saturates due to the geometric overlap between the H^- beam and the laser.

MULTI-PASS BEAM COOLING

H^- ions that remain unstripped after the first pass are recirculated to pass again through the laser sculptor. Recirculation enables the phase space depleted on the first pass to be repopulated. In this way, a slow extraction of the full beam is obtained over multiple turns, without loss of particles and the extracted beam has reduced emittance. The H^0 beam is stretched in time due to the multi-turn extraction, however, when recaptured as protons after foil stripping in a second circular storage ring, the beam is recompressed.

A racetrack lattice was designed in MADX and implemented in BDSIM with a laser sculptor in a low dispersion insertion region of the storage ring, as in Fig. 5. Beta functions of the lattice agree well between MADX and BDSIM for the tracked H^- ions.

In a simulation starting from the LINAC4 distribution, 8000 H^- ions were injected into the storage ring. After 1000 turns, 58.2 % of the ions had been extracted as an H^0 beam with significantly reduced size as in Fig. 6. The emittance of the H^0 beam is 17.3 % of the circulating H^- beam. This simulation has no scale factor (=1) and E_l = 67.4 µJ. Faster extraction is possible by increasing the laser power.

CONCLUSIONS AND OUTLOOK

A method to laser sculpt H^0 beams from H^- has been proposed based on a novel interaction geometry in a storage ring. Simulations show a clear reduction in the transverse size and emittance is achieved for a single-pass of the laser and for multi-turn extraction. Laser sculpting enables the creation

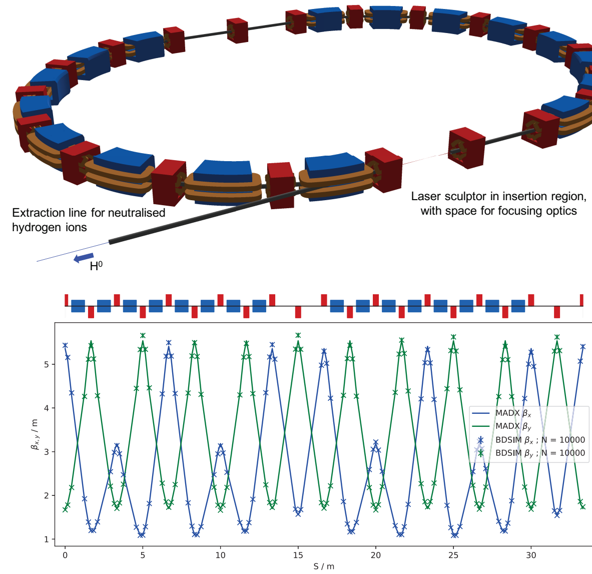

Figure 5: Racetrack storage ring with laser sculptor in red (beam pipe section invisible for visualisation) and the extraction line for neutralised hydrogen ions, emerging in blue.

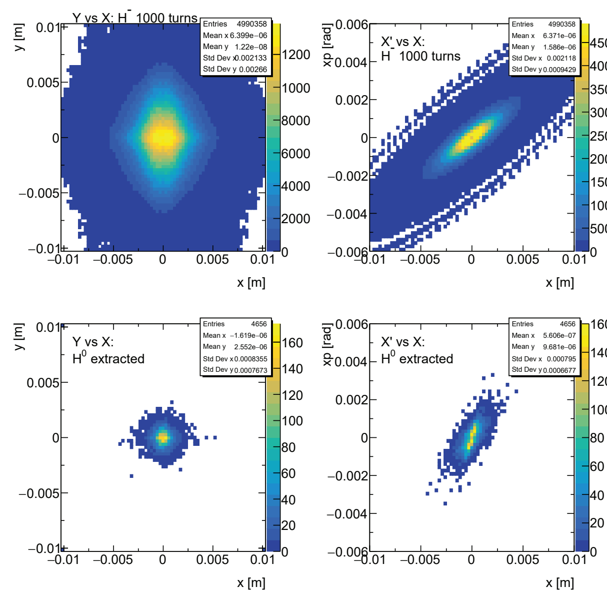

Figure 6: H^- beam for 1000 turns of the racetrack is extracted as H^0 by the laser sculptor with reduced size and emittance.

of very low emittance H^0 beams suitable for capture in a subsequent proton accelerator. In future, these initial simulations will be extended to optimise the interaction optics and H^0 yield, in a design study towards a potential experimental demonstration of laser controlled beams.

ACKNOWLEDGEMENTS

Work supported by UK STFC grants ST/N00175/1, ST/P003028/1 and ST/P00203X/1. We thank T. Hofmann and the LINAC4 team for the input beam distribution and W. Shields for ion rigidity corrections in BDSIM.

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