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THE LIGHT BEAMLINE AT GSI: SHAPING INTENSE MeV PROTON BUNCHES FROM A COMPACT LASER-DRIVEN SOURCE

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Abstract

The LIGHT collaboration has constructed a laser-driven proton beamline at GSI Darmstadt, consisting of a TNSA (target normal sheath acceleration) stage as proton source, a pulsed solenoid for collimation and energy selection as well as a radiofrequency cavity for phase rotation of the bunch. After the successful commissioning and characterization of this beamline, a first extension is now planned to perform phase focusing experiments, leading to intense proton bunches with energies of 8 MeV in a peaked spectrum with only few percent energy spread, particle numbers exceeding 10^9 protons and shortest bunch durations in the sub-nanosecond domain, ranging down to 100 picoseconds.

INTRODUCTION

Nowadays, ion acceleration techniques by relativistic laser matter interactions are able to provide compact, high intensity ion sources in the multi-MeV energy region. Especially the mechanism of *target normal sheath acceleration* (TNSA, [1]) is well understood, routinely used and representing a reliable laser-driven ion source. Typically, protons are the dominant ion species within the acceleration process. The unique beam parameters - like the ultra-low emittance [2], the high particle numbers up to 10^{13} and the initial temporal bunch length in the (sub-)picosecond domain - give rise to manyfold possible applications, as presented in recent reviews on this special field, e.g. [3].

However, for several applications some properties of these beams are highly problematic: The ions show a large envelope divergence of up to 30 deg and a continuous, exponentially decaying energy spectrum. Furthermore, the intense laser matter interaction causes also the presence of energetic electrons, γ- and x-ray radiation as well as the occurance of a large electromagnetic pulse (EMP).

To face these problems, the LIGHT collaboration (Laser Ion Generation, Handling and Transport, [4]) was formed with the central goal to develope and realize a TNSA-based, laser-driven proton beamline concept for collimated, high-intensity proton bunches in the energy range of 10 MeV with an energy spread of only few percent. The current status of this beamline will be reviewed shortly and its planned further developments presented in the following.

THE LASER-DRIVEN PROTON BEAMLINE AT GSI

The beamline consists basically of a laser-driven proton source (via the TNSA mechanism), a pulsed solenoid magnet and a radiofrequency (rf) cavity. It is located at the Z6 experimental area at GSI Darmstadt and driven by the PHELIX laser. Laser intensities of up to 6×10^{19} W/cm^2 can be reached in the Z6 target chamber and maximum proton energies of 28.4 MeV have been recorded from TNSA experiments. In the energy interval ΔE=(10±0.5) MeV, up to 10^{10} protons can be accelerated with a single laser pulse.

The pulsed solenoid magnet at 8 cm behind the source is used for chromatic focusing of the bunch. In this way it is possible to collimate the targeted proton energy and remove other energies at the same time, resulting in a peaked proton bunch with an energy spread of about 20%. A full characterization of the transport characteristics can be found in [5].

Propagating this bunch over a distance of few meters increases its bunch length to several nanoseconds due to the energy spread. This enables the possibility to perform an efficient phase rotation of the bunch via an applied rf field. Therefore a rf cavity was added at 2 m distance to the source. The cavity is a three gap spiral resonator, running at a frequency of 108.4 MHz, the baseline frequency of GSI's UNILAC accelerator. In total, a potential of more than ±1 MV can be applied to the bunch. Injection at a synchronous phase of Φ_s=-90 deg leads to a reduction of the energy spread (depending on the applied rf voltage U_{rf}). By this, it was possible to shape 9.6 MeV proton bunches with only (2.7±1.7)% energy spread and containing more than 10^9 particles. Detection and characterization of these bunches was done at 3 m distance to the source and results have been published recently in [6].

A schematic of the experimental realization of the beamline is shown in Figure 1. Also indicated is the upgrade, which is forseen for the second half of 2014. This extension will enable a temporal compression of the bunch and is discussed in the next section.

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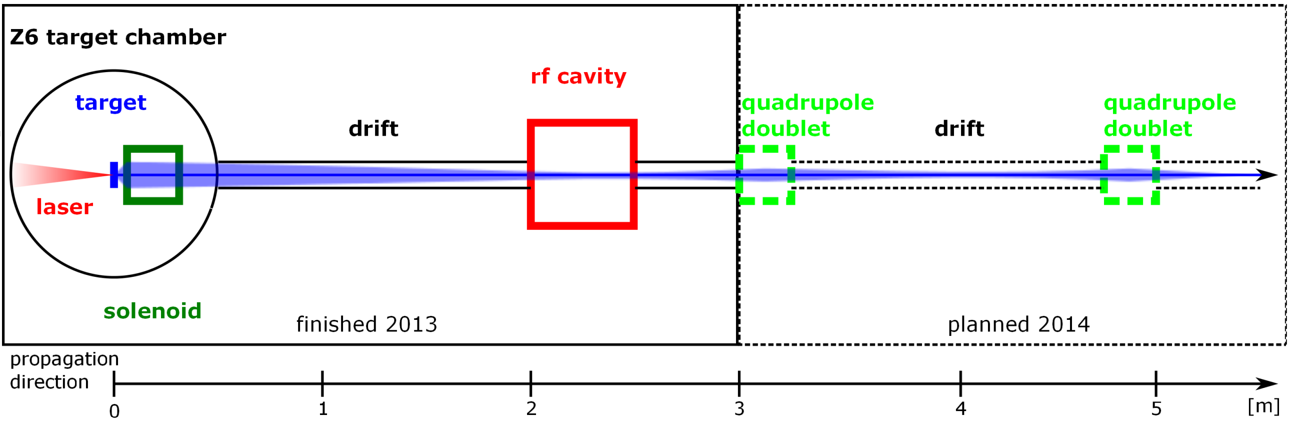

Figure 1: Schematic view of the current LIGHT beamline at GSI Darmstadt and the forseen extensions for 2014.

TEMPORAL BUNCH COMPRESSION VIA PHASE FOCUSING

As the proton bunch is accelerated from the source within a very short time (approx. 1 ps), the synchronous phase of each particle is in good approximation determined by its energy via time-of-flight from source. The resulting very small longitudinal emittance gives the possibility to re-focus the bunch temporally with the help of the rf cavity. On the basis of the experimental results presented in the previous section and the references therein, a simulation study is performed with the *TraceWin* [7] code to model the phase rotation and temporal compression.

The input proton spectrum for the simulation study has been adapted to the characteristics of the experimentally observed spectral shape due to the chromatic focusing with the solenoid, compare [6]: The central part of the bunch can well be fitted with a Gaussian with standard deviation σ=0.7 MeV, while the edges show a smoother decrease in particle intensity. The full bunch is most realistically reproduced by a superposition of two Gaussian distributions, in the case at hand via $2{\times}10^4$ protons in a Gaussian distribution with standard deviation σ=0.4 MeV and central energy E_0=8 MeV and $8{\times}10^4$ protons in a second, superpositioned Gaussian distribution with σ=2.1 MeV and again a central energy E_0=8 MeV. The result is shown in Figure 2(a) and fits well the experimental observations regarding the spectral shape, while the particle numbers are down-scaled for the simulations to a total of 10^5 instead of the full 10^9 protons to keep the simulation time short.

Also illustrated in Figure 2 is the effect of the phase rotation with the rf cavity at injection at a synchronous phase of Φ_s=-90 deg: While (b) shows the case of optimum energy compression of the bunch (totally applied rf voltage: U_{rf}=620 kV), further rotation in phase space with increased rf voltage (U_{rf}=1020 kV) again increases the energy spread, (c), and leads to a situation with faster protons (with respect to the central bunch energy) at the backside of the bunch and slower protons at the front. The feasability of achieving these voltages and the demonstration of increasing the energy spread again at higher rf power has already been experimentally demonstrated, see [6].

After a further drift behind the cavity of 2.5 m, the protons from the back will catch up with the ones at the front, resultig in a very intense, temporally compressed bunch, see Figure 2(d). Our simulations predict minimum bunch lenghts of about 100 ps. Although this bunch will longitudinally defocus again behind this (temporal) focus position due to the energy spread, peak proton currents in the order of 10^{10} ns^{-1}, i.e. 1 A electrical current, can be accessed with this setup at an energy of 8 MeV. Such cannot be accessed with existing conventional rf accelerators and enable the perspective for altering and diagnosing probe samples on sub-nanosecond time scales.

This extension of the beamline also requires additional transverse focusing devices to keep the beam transversely confined. As one possibility, two quadrupole doublets (25 T/m field gradient, 50 mm length and typical FODO configuration) are foreseen to refocus the protons. They are already indicated in Figure 1.

CONCLUSION

A novel hybrid beamline concept is presented, which is based on a laser-driven proton source, using the TNSA mechanism. This source provides large particle numbers of $>10^{10}$ protons in a 1 MeV energy interval around a proton energy of 8 MeV, of which one third can be captured and collimated via a pulsed solenoid. Although the initial large energy spread causes a continuously increasing bunch duration, the special properties of the laser-driven source (acceleration time only approx. 1 ps) enable the possibility of efficient phase focusing of this bunch via a rf cavity at a distance of 2 m to the source and a temporally compressed bunch will be observed at 5.5 m distance. Simulations predict a compression to 100 ps bunch duration, thus providing a unique proton bunch with this compact laser-driven proton beamline.

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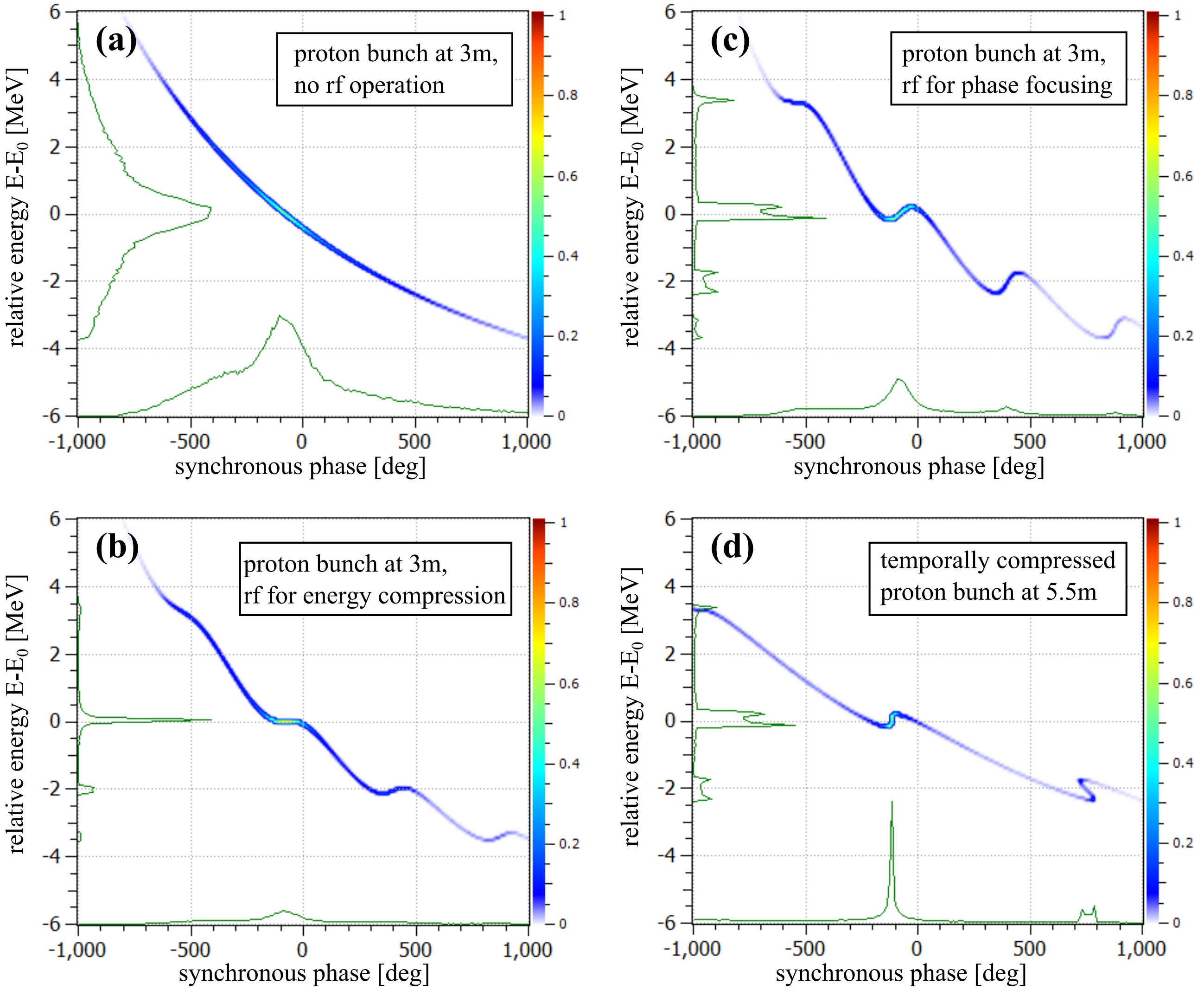

Figure 2: Illustration of the conducted (a,b) and planned (c,d) experiments with E_0 being 8 MeV and the synchronous phase given at the rf frequency of 108.4 MHz. The chromatic focusing of the solenoid results in a peaked but still broad energy spectrum with an energy spread at FWHM of 20% (a). It is possible to reduce this energy spread via phase rotation at an injection phase of Φ_s=-90 deg, as depicted in (b). At a higher applied rf voltage, the energy spread increases again due to an *over-rotation* of the bunch in longitudinal phase space (c). Such a bunch will be temporally compressed along a drift, resulting in sub-nanosecond bunch lengths (d).

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REFERENCES

[1] S. C. Wilks *et al.*, Phys. Plasmas 8, 542-549 (2001)

[2] T. E. Cowan *et al.*, Phys. Rev. Lett. 92, 204801 (2004)

[3] A. Macchi *et al.*, Rev. Mod. Phys. 85, 751-793 (2013)

[4] S. Busold *et al.*, Nucl. Instrum. Meth. A 740, 94-98 (2014)

[5] S. Busold *et al.*, Phys. Rev. ST Accel. Beams 16, 101302 (2013)

[6] S. Busold *et al.*, Phys. Rev. ST Accel. Beams 17, 031302 (2014)

[7] TraceWin at SACM website: `http://irfu.cea.fr/Sacm/logiciels/index3.php`