Plasma Physics and Controlled Fusion

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To cite this article: Vitaly Yakimenko and Tom Katsouleas 2011 *Plasma Phys. Control. Fusion* **53** 085010

IOP PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **53** (2011) 085010 (4pp) doi:10.1088/0741-3335/53/8/085010

Proton-based driver for the plasma wakefield accelerator with TeV reach

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Received 2 September 2009, in final form 2 May 2011
Published 3 June 2011
Online at stacks.iop.org/PPCF/53/085010

Abstract
Many orders of magnitude increase in accelerating gradients were achieved in plasma with laser or charge particle beams, when compared with traditional RF accelerators. The energy depletion of the driving beam ultimately limits energy gain in the single acceleration stage. It was suggested that acceleration to teravolt scale energies is feasible in the single acceleration stage with a proton beam that is similar to one used at the Large Hadron Collider. Existing proton accelerators are unsuitable for driving a linear collider beam due to their average beam power that entails very low luminosity. Here, we discuss the high average power requirement and possible design solutions to overcome these limitations.

Recently, the suggestion was made to use a proton-based driver for the plasma wakefield accelerator (PWFA) to accelerate electron bunches to the energies of interest for the next linear collider [1]. This approach offers several attractions compared with driving the PWFA by electrons:

(1) TeV- and multi-TeV-proton bunches can accelerate electron and positron bunches to TeV range in a single stage.
(2) Proton accelerators operating at several TeV are affordable.
(3) The accumulation of very high intensities of 10^{14} protons potentially could support mega-ampere drive beams.

In this paper, we identify a few shortcomings in existing PWFAs with high-energy proton accelerators and suggest some paths to modifying existing rings that potentially could fit them for the role of an PWFA driver. The issues we discuss encompass average extractable power, longitudinal emittance of the bunch at the final energy, the beam's divergence due to the finite transverse emittance and the relatively low gamma radiation, and the long plasma channel. Each of these items illustrates the limitations of existing machines. We also will demonstrate that these limitations are due to particular designs of colliders having different goals. These shortcomings can be avoided if a multi-TeV proton accelerator, designed to drive a linear collider (LC), is based on a PWFA.

1. Average extractable power of the proton driver and its implication for luminosity

The acceleration rate of existing colliders is very low, and typically, is limited to about 30 min by the ramp time of the characteristics of the superconductive magnets that bend the high-energy particles into circular orbits. Therefore, the average beam power of the beam extracted from such a machine is limited to kilowatt levels. The estimated value of the Tevatron beam is 5 kW. The luminosity of the collider is represented by

$$L = \frac{N^2}{\sigma} f,$$

where N is the number of particles per bunch, f is the collision rate and σ represents the bunch area at the interaction point. It can easily be rewritten using beam power, P:

$$L = \frac{PN}{\sigma}.$$

The Baseline International Linear Collider (LNC) plans to have 50 MW of beam power. Employing a PWFA will need extraction of somewhat higher levels of power to excite the wakefield and to achieve a similar luminosity.

We readily can determine the power that is needed in the proton driver; simulations suggested that 10% efficiency was needed in coupling the proton beam's power to the wakefield. Separate simulations achieved more than 50% coupling power from the wakefield to the witness electron beam [2]. Thus, 1 GW of average power of the proton beam is needed to achieve the ILC's baseline luminosity with the same bunch intensity and size.

However, since only 100 MW of this power will be extracted, an energy-recovery scheme can be employed to decelerate the proton beam after plasma interaction; thereafter, most of the 900 MW 'leftover' power can be reused to accelerate the following bunches. Other scenarios wherein the PWFA extracts close to 50% of the proton power would make energy-recovery optional.

Design solutions for a proton driver with high average power are available in the proposals for a Muon collider where a fast acceleration rate is required due to the short lifetime of muons at rest. Non-scaling fixed-field alternative gradient (FFAG) transport-lattices potentially afford the ability to have a very fast acceleration by a factor of four in energy without changing the magnets' field. A combination of the rapid negative to positive cycling (approximately at 100 Hz) of the normal conducting magnets with fixed-field superconductive magnets will allow acceleration (and deceleration) of the beam from 0.1 to 0.5 TeV in the Tevatron tunnel (figure 1).

The generation of adequate proton-beam intensities at low energies (the injector part of the complex) is already demonstrated [3]. Thus, the spallation neutron source (SNS) has a very similar beam format/power at the 1 MeV/1 MW level.

Accelerating the proton beam in many turns dramatically reduces the length and cost of the RF system compared with that of a single-pass linear accelerator. Each beam will pass ∼500 times through the accelerating cavities, and therefore, an approximately 2 GeV linac will be needed. Compared with an ILC, the cost of this approach is clearly shifted from that of the superconducting RF driver and constructing a long tunnel to the design of the magnet system.

2. Longitudinal emittance and compressibility of the proton beam

The longitudinal emittance of the proton beam is a crucial aspect of the recent proposal. The bunch must be compressed to a fraction of the plasma wave's period, ideally 30–100 μm. The

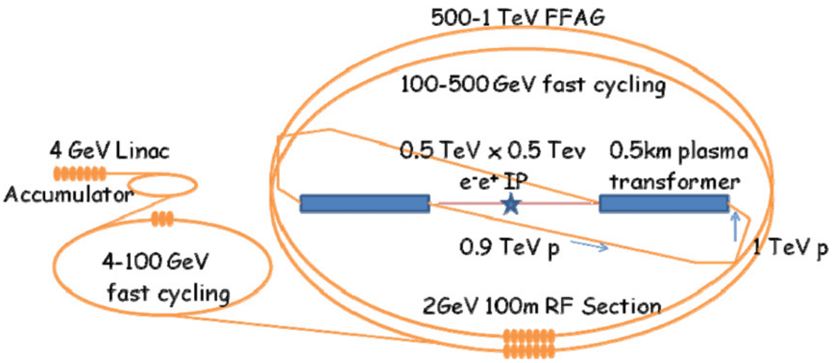

Figure 1. Layout of the high-average beam power proton driver for the PWFA that will fit into the 6.3 km Tevatron tunnel.

(This figure is in colour only in the electronic version)

normalized emittance of 1–3 m eV s is easily estimated to allow such compression at 1 TeV energy while maintaining a reasonable energy spread of 1%.

A longitudinal emittance of 0.1 eV s or higher is typical at existing proton accelerators. This acceptable value for existing colliders is determined by the particular re-bunching of the medium energy. The estimated emittance of the beam coming from the RFQ is 200 KeV deg, or 30 μeV s, for the 200 MHz RFQ.

Whilst the combination of these different measures, including lowering the frequency of the linac and accumulator RF, gradual compression of the bunches, a higher energy linac and accumulator, and using laser striping instead of foil undoubtedly will increase the cost of the injector system, it will dramatically reduce the growth of emittance.

Expectedly, a nanosecond beam will be injected into the rings in the main tunnel. Running the RF slightly of crest (or/and the dedicated RF sections) would allow the introduction of an energy chirp on the beam and its gradual compression to the picosecond level with a properly designed arc-lattice. Final compression is expected to be achieved in the transport channels to the plasma channel because the resulting peak current will create instabilities in the ring.

3. Discussion of parameter set

We selected 1 TeV as the proton energy due to the length of the existing Tevatron complex/tunnel; it is somewhat more than the minimum energy below which the wake-phase velocity is too low and dephasing becomes limiting. This relatively low level of energy leads to low efficiency in energy extraction, and the very challenging requirements of energy recovery in FFAG. A scenario with approximately 2 TeV proton energy might offer a better alternative, and might be necessary to assure the energy upgradability of a linear collider.

A 300–500 m long plasma interaction channel discussed in [1] would require a very strong, complicated, and expensive focusing system to resolve the beam's divergence. Instead, better preserving transverse proton-emittance, shortening the plasma channel using a higher density plasma (shorter proton beam), and increasing the initial energy of the proton beam energy can reduce, if not completely eliminate, the need for transverse focusing.

The accelerated bunch intensity is an important variable that can be attained with the proton driver. More than 10^{14} protons/beam were accumulated at the SNS (simulations [1] were done for 10^{11}). The increase in the charge of the driven bunch offers a large reduction in the power requirements of the collider, and changes considerations of energy recovery and the FFAG.

4. Conclusion

In a brief exercise, primarily conducted during a workshop, and provoked by the presentations on Proton-driven plasma-wakefield acceleration, we demonstrated that existing proton accelerators are unsuitable for driving a linear collider beam due to their low ramp rate and average beam power that entail very low luminosity. However, it may be possible to re-use the tunnel of the accelerators and some of their infrastructure in a modified design that overcomes these limitations. The longitudinal emittance will also restrict our ability to compress proton bunches to the needed values. We offer the findings from the Muon collider project along with the potential to increase the driven beam's charge as a solution to the problem of average power/luminosity.

The degradation of longitudinal emittance during re-bunching is identified, and possible solutions proposed using a lower frequency RF and higher linac energy. Modified parameter sets are needed, with proton charge/energy/lengths specifically designed for this purpose; since they are not limited by optimization constraints of existing colliders, they can offer a more attractive PWFA-based LC.

5. Further research opportunities

Although the lack of short-pulse TeV proton beams and the high cost of creating even test beams for this regime may stunt explorations of this idea, several relevant research fronts could bring it closer to fruition: (1) positron experiments. Since relativistic proton wakes are essentially identical to positron wakes, the positron experiments at the SLAC FACET facility will be invaluable in advancing this concept; (2) low-velocity wakefield studies, especially those demonstrating the usage of tapered plasmas to mitigate phase slippage would also be useful. Such experiments could be carried out with electrons at BNL's ATF; (3) studies on preserving longitudinal emittance, and achieving mega-bunch compression (by factors of 10^6) and (4) particle-in-cell (PIC) simulations with well-developed benchmarked codes.

Acknowledgments

The authors thank participants in the PWFA working group for provoking the exploration of this topic, particularly L K Len, V Litvinenko and C Joshi for very stimulating discussions.

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