Expression of Interest: RF-driven plasma accelerator experiments at NICADD

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Abstract. Magnetized plasma can be used as an accelerating structure capable of supporting large amplitude longitudinal fields which are externally driven by a high-frequency microwave source. Such structures can be used at very high frequencies (hundreds of gigahertz), placing them in the intermediate region between conventional (metallic) accelerators, and laser-driven plasma accelerators. At such high frequencies fabrication of metallic components becomes challenging. Single-pulse heating of the structure also becomes an important issue. On the other hand, if the accelerating structure is the plasma (produced, for example, by a laser pulse) immersed in the magnetic field, then these challenges disappear: (i) plasma supports accelerating waves whose wavelength is determined by its density, not the spatial dimension, and (ii) plasma is the ultimate disposable accelerating structure which can be reproduced at a reasonable repetition rate.

We propose an experiment for the NICADD facility which uses the plasma magnetized in the direction perpendicular to the direction of acceleration. The accelerating field is produced by coupling the external electromagnetic wave into the plasma. This configuration corresponds to the inverse Cherenkov effect in magnetized plasma. The phase velocity of the accelerating wave is equal to the speed of light if the plasma density and the microwave frequency are chosen such that $\omega_p = \omega$, where ω_p is the plasma frequency, and ω is the microwave frequency. By the judicious choice of the magnetic field strength, the group velocity of the accelerating plasma wave can be made very small, so that the incident electromagnetic wave is strongly compressed. This compression results in the high accelerating gradient.

NICADD seems to be an ideal facility to do the proof-of-principle experiments because it has a plasma source (accelerating structure) and a short-bunch photoinjector (beam source for measuring the accelerating field). Microwave source and a magnet need to be added to the facility to enable the experiment.

I INTRODUCTION

The quest to higher accelerating gradients (and, consequently, shorter and more practical accelerators) inevitably points to higher frequencies of the accelerating field. This is because, according to the dark current trapping criterion, the accelerating gradient $W_z < mc\omega/e$, where ω is the angular frequency, and e and m are the electron charge and mass, respectively. In a conventional accelerating structure higher frequencies also imply smaller feature size which are hard to fabricate, and can be easily damaged by single-pulse Ohmic heating and the resulting cyclic stress [1]. Recent experience of operating high-gradient structures at CLIC and SLAC revealed that, over time, they are damaged by the localized breakdowns in the vicinity of irises. Therefore, it appears unlikely that future metallic accelerators will be operated at a shorter than 1 cm wavelength.

At the other end of the frequency spectrum are the laser-driven plasma accelerators. Laser wakefield and plasma beatwave accelerators require short-pulse high power laser pulses because plasma wave is driven via the nonlinear ponderomotive force. Typical plasma densities are of order $10^{17} - 10^{19}$ cm^{-3}, and plasma wavelength $10\mu m < \lambda_p < 100\mu m$. Low laser efficiency and repetition rate are some of the technical challenges on the path to developing a practical laser-plasma accelerator.

We propose an experiment in the previously neglected regime of intermediate frequencies (hundreds of GHz) and plasma densities (of order $10^{14} - 10^{15}$cm^{-3}) where high power microwaves can be directly converted into plasma waves. It is also possible to find the appropriate parameter regime which corresponds to the slow group velocity $v_g \ll c$ of the resulting plasma waves. The incident radio-frequency pulse is compressed in the plasma by the factor $c/v_g \gg 1$, and converted into a predominantly longitudinal wave capable of accelerating charged particles to high energies. Therefore, plasma can serve as both the power compressor, and the accelerator.

The proposed magnetic configuration described in Sec. II uses magnetic field which is perpendicular to the acceleration direction. Injecting an intense electromagnetic wave into the magnetized plasma and using it to accelerate particles is an inverse process to the Cherenkov radiation in magnetized plasma described by Yoshii *et. al.* [2]. The electromagnetic wave is injected at the plasma frequency $\omega = \omega_p$. Magnetic field of arbitrary strength can be used in an Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP).

II INVERSE CHERENKOV ACCELERATOR IN MAGNETIZED PLASMA (ICAMP)

In this Section a microwave-driven plasma accelerator is described. The goal is to create an accelerating medium (magnetized plasma) with the following electromagnetic properties with respect to the accelerating electromagnetic wave propagating in $x-$ direction. (i) **Low group velocity:** $v_g = \partial\omega/\partial k \ll c$. This enables significant pulse compression, making the energy density inside the plasma much higher than in the transporting waveguide. (ii) **Mostly longitudinal polarization:** $E_x \gg E_z, E_y$. Such a wave is capable of accelerating particles, and has a high shunt impedance. (iii) **Luminous phase velocity:** $v_{\rm ph} = \omega/k = c$ is equal to the speed of light. This property is essential for accelerating particles to relativistic energies. It is also important for high coupling efficiency from vacuum to plasma (impedance matching).

It turns out that such a configuration was already considered by Yoshii *et. al.* [2] for generating high power radiation. Cherenkov wakes with luminous phase velocity in $x-$ direction are excited by a short particle or laser beam in the plasma immersed in uniform magnetic field $\vec{B} = B_u \vec{e}_z$. It was clearly demonstrated [3] using 2-D particle-in-cell simulations that a short particle bunch moving perpendicularly to the magnetic field excites a slowly propagating electromagnetic wave in magnetized plasma. Of course, any radiation source which uses the kinetic energy of a charged particle can be operated "in reverse" and used as an accelerator. In an accelerator the externally supplied energy of the electromagnetic field is transferred to the charged particle bunch. To our knowledge, the idea of injecting microwaves into the magnetized plasma with the purpose of particle acceleration via the inverse Cherenkov mechanism is put forward for the first time.

PIC simulations using the one-dimensional version of the Virtual Laser Plasma Laboratory (VLPL) code developed by A. Pukhov were carried out. We modeled the coupling of a planar electromagnetic wave incident from vacuum region into the plasma. Wave frequency $\omega = \omega_p$ matches the plasma frequency, and its amplitude $eE_y/mc\omega = 0.01$. Plasma is magnetized in $z-$ direction, with $\vec{B} = B_u \vec{e}_z$, where $eB_u/mc\omega_p = 0.3$. The microwave pulse duration is $T = 100\lambda_p/c$, where $\lambda_p = 2\pi c/\omega$. Plasma occupies the region $110 < X/\lambda_p < 120$.

Three snapshots are shown in Fig. 1. At $t = 0$ [Fig. 1(a)] the electromagnetic pulse approaches the plasma from the left. By $t = 100\lambda_p/c$ [Fig. 1(b)] most of the microwave pulse had entered the plasma and converted into the (primarily longitudinal) Cherenkov wake. The compression factor is of order 10. The ratio between the longitudinal electric field in the plasma E_x in the plasma and the transverse field in vacuum (and in the plasma) is about 3.5. Therefore, ICAMP has a high shunt impedance: most of the field energy is participating in particle acceleration. At a later time $t = 200\lambda_p/c$ [Fig. 1(c)] almost all electromagnetic energy had moved out of the plasma. Very little absorption or reflection is observed.

We have also verified that the phase velocity of the Cherenkov wake is exactly equal to the speed of light by measuring its wavelength in the plasma. We found that $\lambda = \lambda_p$, so that $v_{ph} = \lambda\omega/2\pi = c$. The exact matching of the refraction index between the magnetized plasma and vacuum is responsible for the high coupling efficiency from vacuum into the plasma.

Theoretically, phase velocity is expected to be equal to the speed of light for $\omega = \omega_p$. This can be seen from the well known dispersion relation of the extraordinary (XO) EM wave propagating perpendicularly to the magnetic field:

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_H^2}, \tag{1}$$

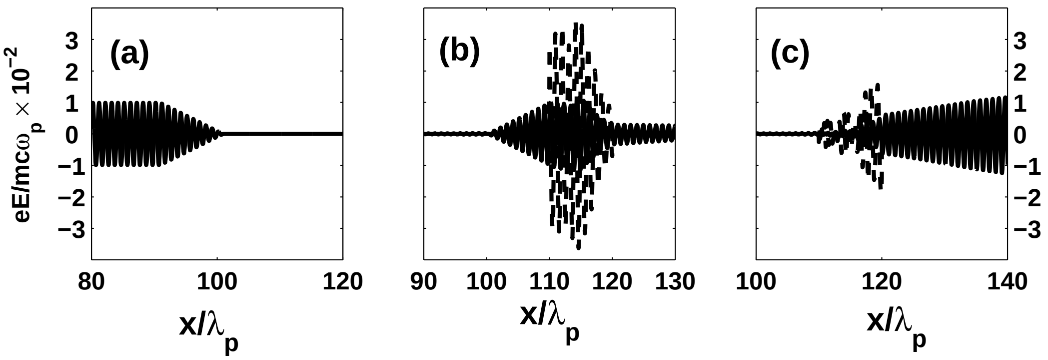

FIGURE 1. Cherenkov wakefield accelerator in magnetized plasma. Magnetic field $\vec{B} = \vec{e}_z B_u$, $eB_u/mc\omega_p = 0.3$. Plasma in region $110 < x/\lambda_p < 120$. Electromagnetic wave with $\omega = \omega_p$ and $eE_y/mc\omega = 0.01$ is incident from vacuum. Transverse (E_y) and accelerating (E_x) electric fields at different times: (a) $t = 0$, (b) $t = 100\lambda_p/c$, and (c) $t = 200\lambda_p/c$. Solid line: E_y, dashed line: E_x.

where $\omega_H^2 = \omega_p^2 + \Omega_u^2$ and $\Omega_u = eB_{\rm u}/mc$. Therefore, $kc = \omega$ for $\omega = \omega_p$. The projected group velocity is $v_g/c = \Omega_u^2/\omega_H^2$. For the presented simulation parameters $v_g/c \approx 0.1$ in good agreement with the simulation results.

It is instructive to translate the simulation results presented in Fig. (1) into physical numbers by assuming that $B_u = 1$ Tesla, $\omega/2\pi = 100$ GHz (or $\lambda = 3$ mm), and $n_p = 10^{14}\text{cm}^{-3}$. Assuming that the plasma area is $\lambda^2 = 0.1\text{cm}^2$, the incident microwave power is about 3MW. The wavebreaking field is about 1 GV/m, and the simulated accelerating wake is 36 MV/m. Increasing the incident microwave power to 300MW should increase the accelerating gradient to about 360MV/m.

Viability of the ICAMP for high energy physics applications depends on whether electrons can gain energy from the accelerating field faster than losing it in the form of a synchrotron radiation. For ultra-relativistic electrons the radiated power is given by $P = (2/3)e^2 c\gamma^4/\rho^2$, where $\rho = \gamma c/\Omega_u$ is the radius of curvature. For $\gamma = 10^5$ and $B_u = 1$T we find that $\rho = 160$m. Therefore, in a $L = 1$m long accelerating section the beam is transversely displaced by $\delta y = L^2/2\rho \approx 30\mu$m. Synchrotron loss per unit length is given by

$$\frac{dP}{dz} = \frac{2}{3}\gamma^2 mc^2 \left(\frac{\Omega_u^2 r_e}{c^2}\right) = 3\ \text{MV/m} \left(10^{-10}\gamma^2 B_u^2\right), \qquad (2)$$

where $r_e = e^2/mc^2$ is the classical electron radius, and B_u is measured in Tesla. Thus, for $B_u = 1$T and $\gamma = 10^5$ synchrotron losses are about 1% of the energy gain due to acceleration. This constraint on the performance of the inverse Cherenkov accelerator becomes significant beyond 100 GeV unless a denser plasma (or lower magnetic field) is used.

III CONCLUSIONS

The inverse Cherenkov accelerator aims at solving the following problem: how to efficiently couple high-frequency microwave radiation into the plasma, thereby transforming it into a longitudinal wave capable of accelerating high energy electrons. ICAMP has the following features: (1) luminous waves with $\omega = kc$ are possible; (2) there are no reflections upon coupling from vacuum into the plasma; (3) group velocities scale as Ω_u^2/ω_p^2; (4) electric field in the plasma is primarily longitudinal; (5) very large energy density compression is achievable. It should be possible to realize ICAMP at the NICADD experimental facilities which has both the plasma source and the bunched electron beam for diagnosing the accelerating field. A microwave source and a magnet would have to be added to the facility.

REFERENCES

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