DEVELOPMENT OF RF SYSTEM FOR MEASURING PLASMA DENSITY MODULATION OF PROTON BEAM-DRIVEN PLASMA WAKEFIELD*

S. Y. Kim, M. Chung†, Ulsan National Institute of Science and Technology, Ulsan 44919, Korea

Abstract

Proton beam-driven plasma wakefield acceleration technique using the proton beam of Super Proton Synchrotron (SPS) at CERN has been actively researched these days. Plasma density modulation due to the proton beam will generate high-gradient's electric field within the modulated plasma. The key role is Self-Modulation Instability (SMI) of the long proton beam. To understand SMI phenomena, we have studied RF system such as heterodyne system for measuring modulated plasma density caused by the SMI. In this work, we design the details of the RF system and optical system of focusing millimetre-sized electromagnetic wave using CODE V and plasma-electromagnetic wave interactions using simulation tools.

INTRODUCTION

The Proton beam-driven plasma wakefield acceleration (PBD-PWFA) is actively investigated in CERN [1]. PWFA is the innovative acceleration technique in that the plasma is used as the accelerating medium, which is different from the conventional RF accelerating cavity. The main cause of generating plasma wakefield is the plasma density modulation due to the driving proton beam. Since the key parameter of generating high-gradient's plasma wakefield is the longitudinal length of the driving beam, it has to be equal to the wavelength of the plasma oscillation [2, 3]. Initial proton beam from the Super Proton Synchrotron (SPS) does not meet the condition due to its long length. However, after injecting into the plasma, it is automatically split into micro-bunches, so that their length will be same to the wavelength of the plasma. This is so called Self-Modulation Instability (SMI), and due to the SMI, accelerating gradient of the plasma wakefield increases dramatically.

Achievement of tens of GV/m by the plasma wakefield and the principle of wakefield have been demonstrated by various simulations [4] and experimental results [5], but the plasma density modulation of the plasma wakefield has not been directly observed by the experiment. Therefore, to measure the plasma density modulation within the plasma and to accomplish the proof-of concept experiment, we are implementing the simulations and diagnostic system using the electromagnetic wave. In this work, designed RF heterodyne diagnostic system and simulation results are presented. Further, focusing millimetre-sized electromagnetic wave lens design is also described.

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† mchung@unist.ac.kr

BASIC THEORY AND SIMULATION

For measuring the plasma density modulation in the plasma wakefield experiment, RF heterodyne system has been designed. Basic concept of the diagnostic system is to detect the source signal transmitted or reflected from the modulated plasma when the electromagnetic wave signal is passing through the layers including the plasma regime. Figure 1 is the schematic view of multi-layers for the electromagnetic wave simulation. Also the parameters such as refractive indices and lengths of the layers are shown in the Table 1.

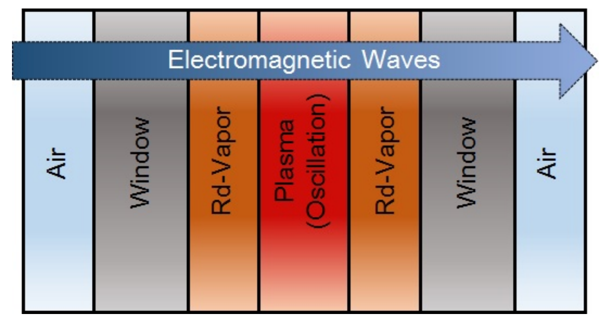

Figure 1: Schematic view of layers for the electromagnetic wave simulation.

Table 1: Index of Refractive and Length of Each Medium for the Simulation

Medium	Refractive index	Length
Air	1.0001	
Window	1.1 (Assumption)	10 mm
Rd-Vapor	1 (Assumption)	10 mm
Plasma	0 ~ 1 (with respect to the source frequency)	1 mm

In this simulation, the key parameter is plasma oscillation frequency. According to the plasma density, plasma angular frequency is determined by the Eq. (1) where the plasma density is expressed as n_e. Plasma oscillation frequency can be obtained by the angular frequency divided by 2π.

$$w_{pe} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}. \quad (1)$$

When the frequency of source signal is same with the plasma oscillation frequency, electromagnetic wave cannot propagate into the plasma but will be reflected by the plasma cut-off effect. By using the cut-off effect of the plasma, diagnostic system is devised to measure the transmitted or reflected signal of the electromagnetic wave. Furthermore, it is expected that the range of plasma oscillation frequency from the modulated plasma is 200~300 GHz. To proceed the simulation before fabricating the diagnostic system, it is assumed that all layers are uniform, lossless media. Plasma layer is also uniform medium, but the density is changed. Adapted source frequency of the electromagnetic wave is 300 GHz. Transmission and reflection coefficients are calculated under the electromagnetic boundary conditions of each layer.

Also, since the plasma is continuously oscillating, plasma density is not a stationary. Therefore, it is assumed that the density change in the plasma layer is a periodic motion as a sinusoidal wave with the frequency of 237 GHz (Fig. 2).

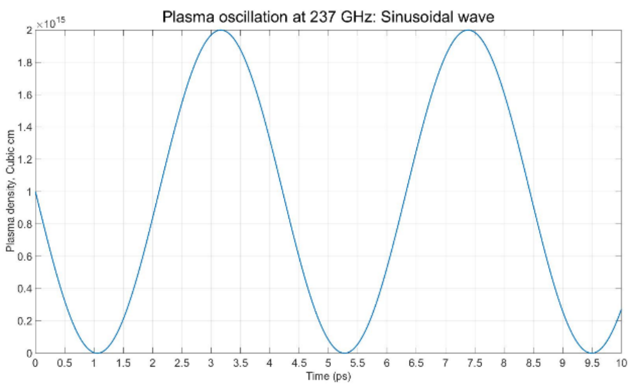

Figure 2: Plasma density oscillation at 237 GHz. Range of plasma density is in the order of 10^{13}~$10^{15}/cm^3$.

Once the electromagnetic wave propagates into the modulated plasma, it will be transmitted or reflected from the effect of plasma cut-off. The critical plasma density for the cut-off effect is $1.1162 \times 10^{15}/cm^3$ when the source frequency is 300 GHz. Related coefficients graph is described in Fig. 3. Period of the oscillation is 4.22 ps. Maximum and minimum transmission coefficient is 0.9398, 0, respectively.

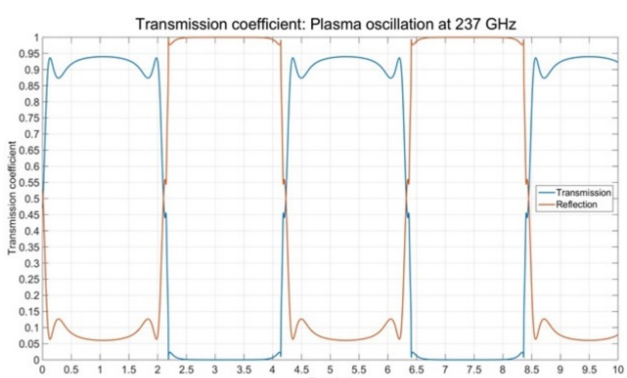

Figure 3: Transmission and reflection coefficients of the electromagnetic-wave by the plasma density modulation.

Figures 4a and 4b are describing the transmission and reflection coefficients in terms of the frequency. When the plasma is oscillating with 4.22 ps, coefficients are determined by the plasma frequency. Through the Fig. 4b, oscillating patterns can be checked. It is due to the sine and cosine terms in the calculation formula. Simple example is demonstrated in the Griffith's Introduction to Electrodynamics [6].

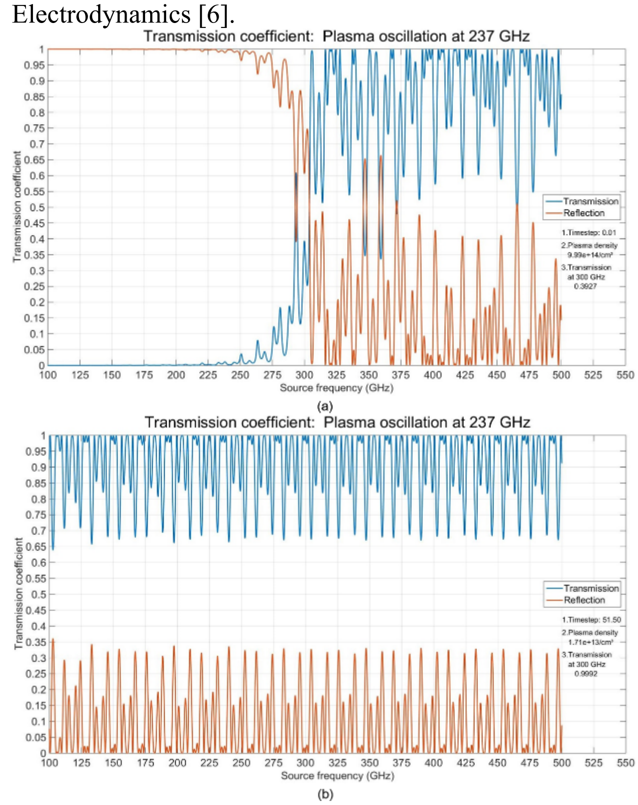

Figure 4: Transmission and reflection coefficients of the source signal. (a) Plasma frequency is $10^{15}/cm^3$ at 0.001 ps. (b) Plasma frequency is $1.71 \times 10^{15}/cm^3$ at 5.15 ps.

With the result of simulations, input and output (measured) powers of the source signal can be determined by the calculated coefficients. However, for the accurate calculation, loss terms of the media should be considered.

DESIGN OF RF SYSTEM AND FOCUSING LENS

RF Heterodyne System

Through the simulation results, it is expected that the transmitted or reflected source signal cannot be measured directly by the fast-scope or signal analyser due to its frequency (See the Figs. 3 and 4. Time scale is picoseconds). Thus, we have to design the RF heterodyne system to catch the source signal effectively. Heterodyne system uses frequency mixing to convert a received signal to a fixed intermediate frequency (IF) which can be more conveniently analysed than the initial source frequency [7]. In order to produce IF, local oscillator (LO) is needed. In this diagnostic system, it is proposed that sub-harmonic RF mixer is used to down convert the initial 300 GHz frequency to 1 GHz. Sub-harmonic RF mixer is the frequency mixer that mix the original source signal and

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doubled LO frequency. Afterward, mixed frequency is down converted to IF. Designed RF heterodyne system is shown in Fig. 5.

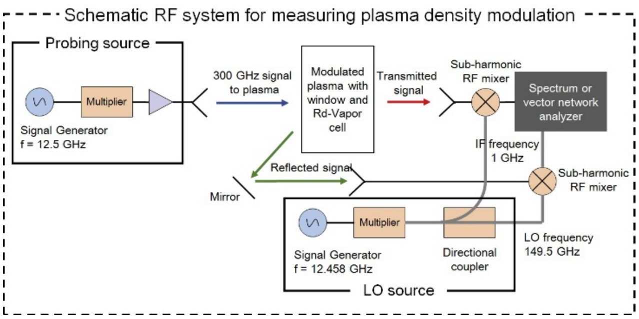

Figure 5: Schematic RF heterodyne system for measuring plasma density modulation.

When the source frequency is transmitted, it is mixed with the LO by the sub-harmonic RF mixer. In the same manner, reflected source frequency is also mixed with the LO split by the directional coupler. Measured intermediate frequency is analysed by the signal (spectrum) or vector network analyser.

Focusing Lens Design

In order to measure the plasma density modulation, it is essential to fabricate the focusing electromagnetic wave lens to millimetre-size. From the wavelength of plasma oscillation is 1.2 mm, focused spot size of the electromagnetic wave has to be equal to or less than the wavelength of the plasma oscillation (see Fig. 6). For designing diagnostic system, we are considering only the single regime of plasma density modulation, and measuring the change of its density. If the focused signal spot size is bigger than 1.2 mm, measured signal cannot be accurately analysed due to the signal composition of high and low density plasma. Figure 7 is designed focusing lens for 300 GHz electromagnetic wave. Initial radius is 2.8 mm, and fo- cused radius is 0.92 mm. From the simulation results, it has to be improved as the lens size, focal length of each lens and the spot size of 0.5-millimeter radius.

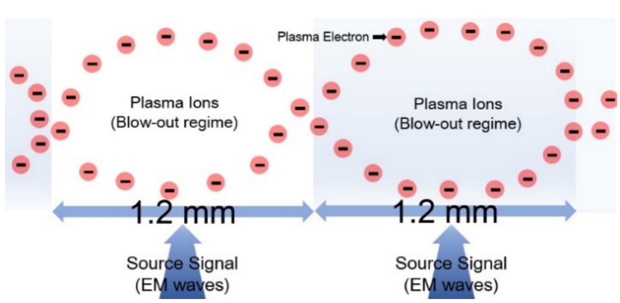

Figure 6: Schematic view of requirement for the experiment.

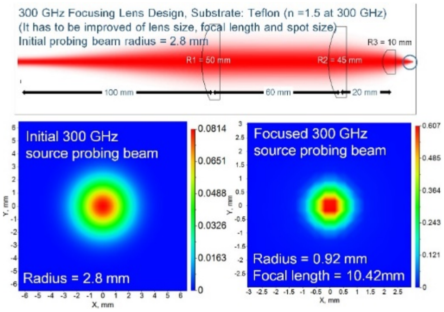

Figure 7: Pre-designed focusing lens for 300 GHz electromagnetic wave.

FUTURE WORKS

As in the future works, we will further investigate the simulation for electromagnetic wave-plasma interaction to measure the transmitted and reflected source signal. Since the results in this paper are in case of lossless, simulation of real situation including loss and refractive indices of the medium will be proceeded. Moreover, plasma layer is also non-uniform in accordance with its modulation so that the proper electromagnetic boundary condition should be applied. Furthermore, considering the domain of received signal because of the size of receiving antenna, spatial behaviour of electromagnetic wave will be demonstrated, and coefficients has to be calculated under the complemented condition. In addition, details of RF components such as multiplier, power amplifier and sub-harmonic RF mixer will be determined with upcoming the simulation results. Lens design to focus 1 mm-sized electromagnetic wave will also be implemented by using CODE V simulation tool.

ACKNOWLEDGEMENT

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REFERENCES

[1] A. Caldwell, K. Lotov, A. Pukhov and F. Simon, " Proton-driven plasma wakefield acceleration", *Nature Physics*, vol. 5, p. 363, Apr. 2009.
[2] A. Caldwell *et al.*, "AWAKE Design Report: A proton-beam plasma wakefield acceleration experiment at CERN", CERN, Geneva, Switzerland, Rep. CERN-SPSC-2013-013, Sep. 2013.
[3] N.Kumar, A. Pukhov and K. Lotov, "Self-modulation instability of a long-proton bunch in plasmas", *Phys. Rev. Lett.*, vol. 104, p. 255003, Jun. 2010.
[4] J. Vieira, W. B. Mori and P. Muggli, "Hosing instability suppression in self-modulated plasma wakefields", *Phys. Rev. Lett.*, vol. 112, p. 205001, May. 2014.
[5] M. Litos *et al.*, "High-efficiency acceleration of an electron beam in a plasma wakefield accelerator", *Nature*, vol. 515, pp. 92-95, Nov. 2014.
[6] D. J. Griffith, "Introduction to Electrodynamics 3rd", Upper Saddle, NJ, USA: Prentice-Hall, 1999, p. 413.
[7] Superheterodyne receiver, https://en.wikipedia.org/wiki/Superheterodyne_receiver/