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A GROUND EXPERIMENTAL APPROACH TOWARD UNDERSTANDING MYSTERIOUS ASTROPHYSICAL FAST RADIO BURSTS

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Abstract

The Fast Radio Bursts are astrophysical events that get much more attentions that increases year by year, due to their mysterious properties of signals. The major properties of signals include a class of the brightest astrophysical events, short durations of emissions, and larger dispersion measures than the known short duration events observed so far. Interestingly, the large values of dispersion measures suggest the existence of abundant plasma around the parent bodies of emissions. To have a better understanding of basic mechanism of the Fast Radio Burst emissions, we initiated a ground-based research project at our 100 MeV electron LINAC facility, in combination with the high-beta plasma generation knowledge matured also at Nihon University, that mimics plasma fields in space. In this presentation, we overview our project and report on the status of the experiment for the induced enhanced emissions from integrated iterative interactions with plasma fields.

INTRODUCTION

Recently the astrophysical events named “Fast Radio Bursts” get much attention owing to their mysterious signals. The properties of the Fast Radio Bursts events include the milliseconds-scale short emissions and their brightness that is classified as a class of highest emissions ever observed. Therefore the Fast Radio Bursts are totally distinguished from the known astrophysical events. The signal was initially reported in 2007 [1], and more people started paying attentions after the report of four additional signals in 2013 [2]. Although the detection of signals accompanies difficulties due to their sudden occurrences and short emissions, the number of the observed events increases gradually year by year. It is worth mentioning that there appeared interesting papers in these years, including the signals from our Milky Way in 2020 [3, 4], over 500 events reported in 2021 [5], and also the detail analyses of signal time structures within milliseconds durations [6–8]. Although there have been significant progresses in observations regarding the Fast Radio Bursts, we still need much more information to understand their general features of emission mechanism that are still veiled in mystery (see e.g. this review article [9]).

One of the interesting progresses understanding the typical properties of Fast Radio Bursts is the implication of abundant plasma existence around the signal sources or parent bodies. The dispersion measure of signals is one of the important measure classifying the parent bodies of emissions. When a radio signal penetrate through ionization regions, the signal suffers from a delay depending on its frequency. Hence a large dispersion measure suggests the existence of abundant plasma fields. For the Fast Radio Bursts, the observed dispersion measures are generically larger than those of the Galactic pulsers whose emission durations are the similar milliseconds-scales (see this review [10]). On the other hand, there are few known events emitting repeatedly, one of which was observed by the European Very Long Baseline Interferometry so that the position of the source was detected at a satisfactory accuracy [11]. After the observation, the other research group reported that the detail analysis of the polarization with the Faraday rotation measure for this event concluded the existence of an extreme and dynamic magneto-ionic environment around the source [12].

Once the high-energy charged particles enter into electromagnetic fields including plasma, the emissions occur as a result of interactions. Recently, there appeared the reports suggesting the existence of the high energy astrophysical bodies called “PeVatrons” where the accelerated particles reach the PeV scale, by observing the untra-high energy γ-rays [13, 14]. Together with the fact that the synchrotron radiations are observed from many directions, we have no doubt that high-energy accelerated particles are ubiquitous in space.

To challenge the mystery of the Fast Radio Bursts, we have initiated a laboratory astrophysical project at the Nihon University, by reproducing the properties of the events on the ground. Especially, we pursue the possibility of ultra-bright emissions from the integrated iterative interactions between high-energy charged particles and plasma fields. We believe that the repeatable experiments on the ground provide the detail data enough to help understanding the basic mechanism of the mysterious events in space. In this paper, we first introduce the property of our accelerator system and the plasma generation method suitable for this project, and then illustrate our plan for the interaction experiment and also the current status of preparation.

EXPERIMENTAL BACKGROUND

We have the linear accelerator at Nihon University, where electrons are accelerated upto 100 MeV. We use three normal conducting tubes for the 2.856 GHz RF accelerations whose

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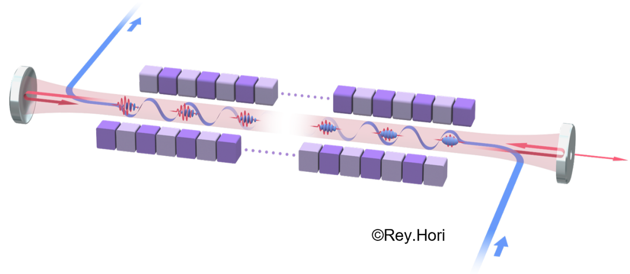

Figure 1: A schematic of the oscillator FEL.

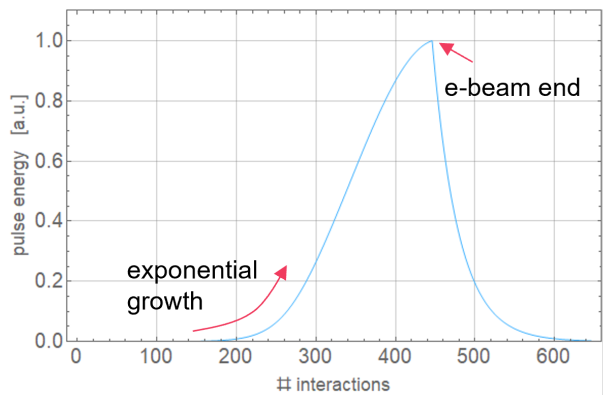

Figure 2: An example of pulse growth respecting the oscillator FEL [15].

powers are supplied by two Klystrons. One of the interesting property of our system is the generation of slightly long electron pulse trains reaching over 50,000 pulses at 2.856 GHz, that is recognized as a longer pulse train among usual normal conducting acceleration systems. This property is an advantage for experiments that need the integrated iterative interactions between relativistic electrons and mediums, hence is good for our project requiring interactions with plasma fields.

For a better understanding, we illustrate the oscillator free electron laser (FEL) as an application of the integrated iterative interactions. We generate a high energy femtoseconds-scale mid-infra-red pulses at this FEL by having the iterative interactions between electron pulses and a self-generated light pulse as the medium. As the schematic illustration shown in Fig. 1, when the electron beam interacts with the periodic magnetic circuit, a monochromatic light pulse is generated. The generated light pulse travels inside the resonator consisting of two concave mirrors, and then re-interacts with the synchronized next coming electron pulse. After over 400 iterative interactions at our system, the resultant light pulse grows exponentially through the interactions where the strong electromagnetic fields make the electron pulse to have a density modulation causing the coherent non-linear emissions. In Fig. 2, we show the simulation result of the paper [15] for a better understanding of this exponential growth as the interaction proceeds. We expect a similar, but not the exactly same, integrated iterative interaction that would occurs even when using a plasma field as the medium.

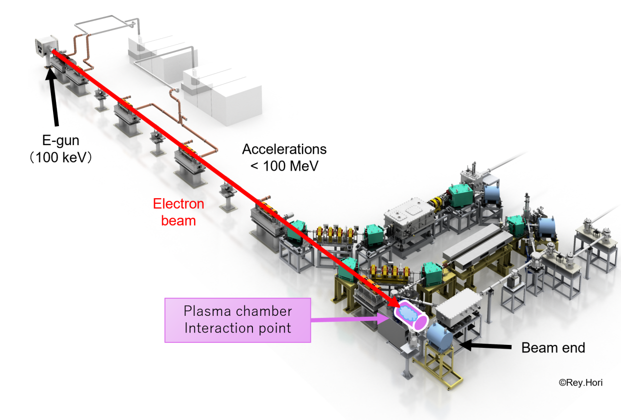

Figure 3: A schematic of the interaction experiment with plasma fields at the accelerator facility.

For the plasma generation, the plasma β is one of the important measures classifying properties of plasma fields, that is defined by the ratio between the thermal and the magnetic pressures. Especially, the values of plasma β are larger then unity for most of the plasma fields in space. In the plasma experiments, the field-reversed configuration (FRC) is a well-developed example for the realization of a high plasma β (see e.g. this review [16]). At Nihon University, we have the long-term experience of the FRC plasma field generations, applications and their handling with the over meter-sized equipments (see this article [17]). So it is our advantage that we already possess the matured knowledge and technology of the high β plasma generations suitable for the current project. Here we plan to employ a generation method inspired by the FRC, realizing a high plasma β that cover a lot of the interaction territory.

CURRENT STATUS OF PREPARATION

We are now installing the plasma chamber where the FRC-inspired plasma is generated and the accelerated electron beam interacts with the plasma field. The schematic picture for the installation is illustrated in Fig. 3. We expect that the signals are generated from the interactions whose frequencies may stay around broad GHz regions, and also allowing to reach the THz region. The frequencies of signals are not determined only by the plasma average frequencies related with their densities since the plasma fields can be modulated through the interactions with electron beams. So we employ a plasma chamber made by ceramic shown in Fig. 4, where alumina of ceramic is mostly transparent against RF including the THz region.

We plan to measure the signals of interactions outside of plasma chamber. Although the technologies of the RF detections are quite matured, we need to separate frequencies depending on each detector ability. First we plan to start measuring the signals up to around 10 GHz, where the ultra-wideband antennas (Fig. 5) can be used. For instance, the antennas are designed for signals in the ranges of 900 MHz

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Figure 4: The plasma chamber made of ceramic for the outside detection of radiation signals.

Figure 5: The ultra-wideband antennas for detecting signals from the interactions with plasmas.

to 12 GHz and 400 MHz to 8 GHz respectively in Fig. 5, suitable for our initial trials. The detected signals at antennas are transferred through coaxial cables, and analysed by a spectrometer directory or by an oscilloscope through a wave detector so as to pickup the fast pulse signals. Due to the commercial availability of the antennas, we also plan to measure a rough spatial profile of the signals by multiple measurements surrounding around the plasma chamber.

Currently we put much of our efforts into the plasma generation suitable at the ceramic chamber where the electron beam coincides. Since there exists a large difference between the pressures required for the plasma side and the accelerator side, we make a separation by a thin titan window where most part of the high energy beam penetrates. After fixing the remaining design of the plasma generation and its injection as well as the status monitors, we will install the plasma chamber and start the interaction experiment, that is expected sometime in 2022.

CONCLUSION

We introduce our laboratory astrophysical project mimicking the mysterious Fast Radio Bursts signals on the ground. Our accelerator has a good potential for this project where the integrated iterative interactions between the high energy beam and the plasma fields might be a hint understanding the basic property of the ultra-bright and short emissions. Fortunately, our knowledge and technology of plasma generations are also matured enough to generate the property mimicking plasma fields in space. Hence we have no doubt that we are ready enough to exploit this good opportunity digging into the mysterious astrophysical events.

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