DPIS FOR WARM DENSE MATTER*

Kotaro Kondo†, Brookhaven National Laboratory, Upton, NY 11973, USA;
RIKEN, Saitama, 351-0198, Japan
Takeshi Kanesue, Kyushu University, Fukuoka 819-0395, Japan
Kazuhiko Horioka, Tokyo Instituite of Technology, Yokohama 226-8502, Japan
Masahiro Okamura, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Warm Dense Matter (WDM) offers an challenging problem because WDM, which is beyond ideal plasma, is in a low temperature and high density state with partially degenerate electrons and coupled ions. WDM is a common state of matter in astrophysical objects such as cores of giant planets and white dwarfs. The WDM studies require large energy deposition into a small target volume in a shorter time than the hydrodynamical time and need uniformity across the full thickness of the target. Since moderate energy ion beams ($\sim$ 0.3 MeV/u) can be useful tool for WDM physics, we propose WDM generation using Direct Plasma Injection Scheme (DPIS). In the DPIS, laser ion source is connected to the Radio Frequency Quadrupole (RFQ) linear accelerator directly without the beam transport line. DPIS with a realistic final focus and a linear accelerator can produce WDM.

INTRODUCTION

Warm Dense Matter (WDM) is the state of between a plasma and a solid. Figure 1 represents a map of WDM regime in the density-temperature plane[1]. In a WDM, the potential energy of the interaction is the same order as the kinetic energy of electrons. The physical parameters are high density (0.01 to 1 $\times$ solid density) and low temperature (0.1 to 10 eV) with partial electron degeneracy and strong ion-ion correlation. It is difficult to predict the behavior, because WDM is characterized by many body and disorder system.

However, WDM is not unusual for astrophysics. This is a common state of matter in cores of giant gas planets and white dwarfs. The accurate Equation of State (EOS) of hydrogen in WDM helps us to understand the core structure of Jupiter and Saturn. The total mass and the mass of a core of heavy elements, which are sensitive to EOS of hydrogen, is significant to the planet formation process[2]. In inertial confinement fusion, WDM is the preliminary stages of fuel compression and the behavior is critical point for evaluation of the effects of the blast in the chamber[3].

Although some intense methods by laser, charged particle beams, and pulse power are proposed conventionally, moderate energy ions ($\approx$ 0.3 - 3 MeV/u) is also useful as modest-cost drivers for generating WDM[4]. Direct Plasma Injection Scheme (DPIS), which has been researched at Brookhaven National Laboratory (BNL)[5], is a powerful tool for high current and high charge state heavy ion beam production. The intent of this paper is to show the DPIS has a potential for WDM formation.

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† kkondo@bnl.gov

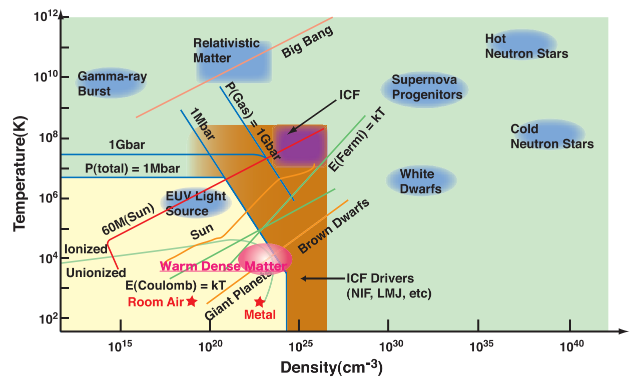

Figure 1: Map of WDM regime in the density-temperature plane[1].

DIRECT PLASMA INJECTION SCHEME FOR WARM DENSE MATTER

DPIS is a combination of Laser Ion Source (LIS) and Radio Frequency Quadrupole (RFQ) linear accelerator without the transport line. The plasma including highly charged heavy ions, which is ablated from a solid target irradiated by a pulse laser, goes into the RFQ directly in an electrically neutral condition and the ions are extracted at the RFQ entrance. RFQ captures beams from low energy region with strong electric focusing force and makes a bunch structure, and the beams are accelerated.

1 bunched beam should be taken from bunched beams at RFQ exit, because we prevent energy injection to a target by multi bunched beams during the hydrodynamic motion for making a well-defined WDM state. Therefore, a RF Kicker is located at RFQ exit to have a 1 bunched beam. After the RF Kicker, a focus system need to be installed because the beam energy density is still not enough to generate WDM. A combination between a focus system and a linear accelerator, which accelerates ion from sub-MeV/u to MeV/u after RFQ, with DPIS can be also a generation method for WDM. A possible DPIS experimental setup with RF kicker and focus system is shown in Figure 2.

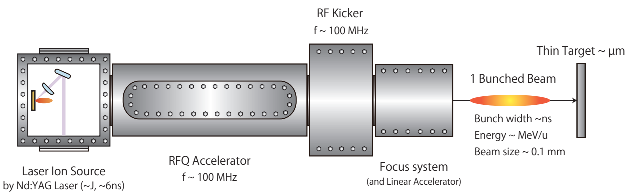

Figure 2: Sketch of DPIS with RF kicker and with focus system for WDM.

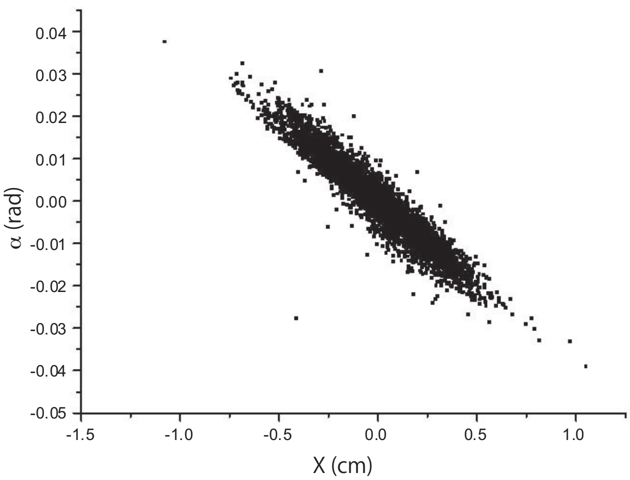

Figure 3: Transverse emittance at the exit of RFQ.

PARAMETER SURVEY WITH 2 DIFFERENT RFQS FOR WDM

We have a parameter survey for 2 existing different types RFQ at BNL[6] and at Institute of Modern Physics (IMP) in China[7] for WDM generation. Enough energy needs to be deposited to a target to raise the temperature of WDM regime. In order to obtain an estimation of WDM generation, it is assumed that the energy density is equal to the energy deposited per the target volume over which the energy is deposited, that a distribution of ion intensity is uniform at the focal plain, and that the final focus size is 100 μm by a focus system after RFQ.

DPIS using Ag^{15+} *for WDM*

New RFQ in BNL, which accommodates q/A = 1/8 particles (q: charge number, A: mass number) supposing Ag^{15+}, was designed. Based on a plasma property data from previous experiments, simulation study was done with a multi species beam tracking cord Pteq-HI[6]. The RFQ operation frequency is 100 MHz, initial injection energy is 900 keV, and the extraction energy is 270 keV/u as shown in Table 1. The transverse and longitudinal emittance at the exit of RFQ are shown in Figure 3 and 4, respectively. From these results, the beam size after RFQ is about 2 mm.

The energy loss rate (dE/dx) of Aluminum is obtained from the SRIM code[8] based on the total Ag^{15+} ion energy of 28.89 MeV after RFQ. An Al target of 1 μm thickness is selected because the bunched beam pulse length is less than the hydrodynamical time scale for this length. The achievable temperature of Al target is given from injection ion number, the energy loss rate and the target volume. Table 1 shows basic parameters of DPIS using Ag^{15+} with a focus system and the achievable temperature. When the beam size can be focused to 0.1 mm, the beam can generate a WDM state with 0.19 eV and solid density.

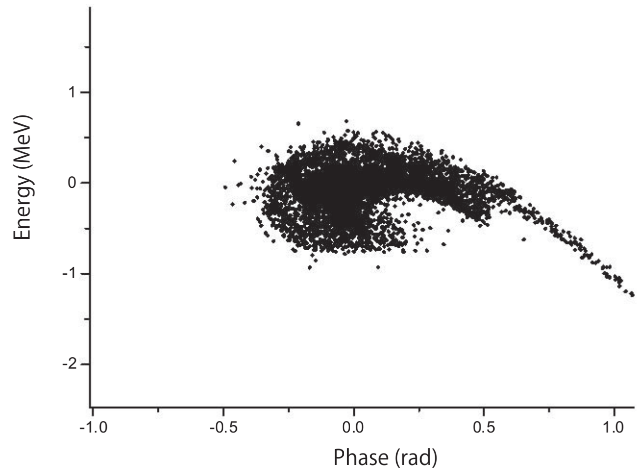

Figure 4: Longitudinal emittance at the exit of RFQ.

Table 1: Basic parameters for DPIS using Ag^{15+} with a focus system and the achievable temperature

Ion	Ag^{15+}
Target	Al
Frequency	100 MHz
Output Energy per nucleon	0.27 MeV/u
Output Ion Energy	28.89 MeV
Peak Current	20 mA
Bunch Length	$\sim$ ns
Minimum Aperture	5 mm
Energy Loss Rate in Al	0.73 MeV/μm
Final Beam Size	100 μm
Al Target Temperature	0.19 eV

DPIS using C^{6+} *for WDM*

DPIS has been researched at IMP for intense heavy ion beam injection for Cooler-Storage-Ring of the Heavy Ion Research Facility in Lanzhou[7]. The main feature of this RFQ is high q/A = 1/2. Based on RFQ in IMP, we have an estimation for WDM study. Tantalum is selected as target, and the injection ion is C^{6+}. Table 1 represents basic parameters of DPIS using C^{6+} and the achievable temperature. As well as RFQ in BNL, the final beam size by a focus system is assumed to be 100 μm, the thickness of the target is 1 μm, and the energy loss rate of Ta is obtained from the SRIM code[8]. In this case, the temperature is estimated to reach 0.74 eV and this is higher than that by BNL RFQ. These results indicate that DPIS with different RFQ can access a wide region of WDM.

Table 2: Basic parameters for DPIS using C^{6+} with a focus system and the achievable temperature

Ion	C^{6+}
Target	Ta
Frequency	100 MHz
Output Energy per Nucleon	0.8 MeV/u
Output Ion Energy	9.6 MeV
Peak Current	20 mA
Bunch Length	$\sim$ ns
Minimum Aperture	6 mm
Energy Loss Rate in Ta	2.9 MeV/μm
Final Beam Size	100 μm
Ta Target Temperature	0.74 eV

CONCLUSIONS

WDM physics is a rapidly growing science field and is strongly related to planetary sciences. We propose WDM formation by Direct Plasma Injection Scheme (DPIS). A parameter survey shows that DPIS with a final focus can produce WDM state. These results indicate that DPIS with different RFQ can access a wide parameter region of WDM.

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