

An accelerator facility for WDM, HEDP, and HIF investigations in Nazarbayev University

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Abstract. Nazarbayev University (NU) in Astana, Kazakhstan, is planning to build a new multi-MV, ~ 10 to several hundred GW/cm² ion accelerator facility which will be used in studies of material properties at extreme conditions relevant to ion-beam-driven inertial fusion energy, and other applications. Two design options have been considered. The first option is a 1.2 MV induction linac similar to the NDCX-II at LBNL, but with modifications, capable of heating a 1 mm spot size thin targets to a few eV temperature. The second option is a 2 - 3 MV, ~ 200 kA, single-gap-diode proton accelerator powered by an inductive voltage adder. The high current proton beam can be focused to ~ 1 cm spot size to obtain power densities of several hundred GW/cm², capable of heating thick targets to temperatures of tens of eV. In both cases, a common requirement to achieving high beam intensity on target and pulse length compression is to utilize beam neutralization at the final stage of beam focusing. Initial experiments on pulsed ion beam neutralization have been carried out on a 0.3 MV, 1.5 GW single-gap ion accelerator at Tomsk Polytechnic University with the goal of creating a plasma region in front of a target at densities exceeding $\sim 10^{12}$ cm⁻³.

1. Introduction

Nazarbayev University in Astana, Kazakhstan, is planning to build a new multi-MV, ~ 10 to several hundred GW/cm² ion accelerator research facility within a few years. The facility will be used in studies of material properties at extreme conditions, for hydrodynamic experiments relevant to ion-beam-driven inertial fusion energy, and other beam applications. This new accelerator facility, which is named Nazarbayev University Research Accelerator (NURA), is conceived to follow one of the two design options described below.

The first and more mature option is a 1.2 MV induction linac with an architecture similar to the Neutralized Drift Compression Experiment (NDCX-II) at LBNL [1, 2], but with two important changes. The second option being considered is a 2-3 MV, ~ 200 kA, single-gap-diode proton accelerator based on an inductive voltage adder. The high current proton beam pulse of ~ 50 ns is focused to ~ 1 cm spot size to obtain power densities of several hundred GW/cm², in order to heat thick targets to temperatures of tens of eV. In comparison to the linac, the ion beam generated by a high-power ion diode typically has higher current but lower brightness (ion temperature of >10 eV instead of 0.1 - 0.5 eV for the linac). The longer pulse length due to the high power diode accelerator is more favorable for studying High Energy Density Physics (HEDP) hydrodynamics at the tens of



nanoseconds time scale and at tens of eV temperature. An innovative solution to shorten the pulse length is needed in order to use a diode accelerator for (sub-ns) isochoric heating of materials at Warm Dense Matter conditions.

In both cases, a common requirement to achieving high beam intensity on target and pulse length compression is to utilize beam neutralization at the final stage of beam focusing. For example, NDCX-II makes use of a neutralized drift section to compress the beam pulse length to sub-ns. The required neutralizing plasma density near the target is $n \sim 10^{13} \text{ cm}^{-3}$. Due to the much higher beam current, the single-gap ion diode may require even higher plasma densities to neutralize the beam charge.

Initial experiments on pulsed ion beam neutralization has been carried out on a 0.3 MV, 1.5 GW single-gap ion accelerator at Tomsk Polytechnic University [4]. This accelerator can deliver hundreds of amperes of proton beam with kinetic energy of a few hundred keV. The goal is to create a plasma region in front of a target, at densities exceeding $n \sim 10^{12} \text{ cm}^{-3}$, for studying beam neutralization and compression. Progress of this experiment and the NURA facility design is reported in this paper.

2. NURA linear induction accelerator

The initial concept for NURA was to use the NDCX-II technology [1, 2] to build an accelerator for WDM studies. A modified design was completed in 2014 for NURA with changes to optimize cost and performance [3]. The main differences from the original NDCX-II design was that NURA will use helium ions (instead of lithium) and electrostatic quadrupole beam transport (instead of solenoids).

Through neutralized drift compression, the 70 nC beam charge at the target will have $< 1 \text{ ns}$ pulse duration, which will be focused to a beam spot size about 1 mm to reach power densities of $\sim 10 \text{ GW/cm}^2$. This short beam pulse can isochorically heat a thin target to a temperature $> 1 \text{ eV}$ before hydro-expansion takes place, thus suitable for warm dense matter (WDM) studies.

In the next section we describe an alternate option for building NURA based on a Single-Gap accelerator (High-Power Diode) design. In this case, a higher beam power can be delivered but over a longer pulse length, thus allowing hydrodynamic motion of the heated target material.

3. NURA single-gap diode accelerator powered by inductive voltage adder

While building a NURA induction linac can be viewed as following the approach of Heavy Ion Fusion (HIF), an alternate option for NURA is to follow the approach of Light Ion Fusion (LIF) which uses magnetically insulated single-gap diode accelerator. It has already been demonstrated that light ion beams can deliver up to several TW/cm^2 to heat targets to hundreds of eVs.

Both the HIF and LIF programs had gone through several decades of hardware and beam physics development. Although HIF is currently the leading concept for ion-beam driven inertial fusion, the light ion diode machine can still be a competitive and cost effective tool in providing high power ion beam pulses for HEDP studies, as long as it is not being evaluated as an inertial fusion driver.

The pulse length from a single-gap diode is typically in the range of several tens of ns (without invoking longitudinal beam compression). In this time scale, the heating process is not isochoric. For example, the sound speed of the gold plasma is about 2.5 km/s. For a few micrometer thick targets, the time scale for hydro motion is about few ns. Thus the single-gap accelerator is not suitable for WDM studies because target heating would not be isochoric. A NURA facility based on the light ion diode accelerator can be useful for experiments to study hydrodynamics of high energy density materials such as acoustics, phase-transitions, plasma formation, implosion, and radiation. Furthermore, the same machine can be used to generate high power electron beams for hydrodynamics and radiation studies.

3.1. Design parameters for a NURA single-gap diode

Several single-gap accelerators using pulsed-power technology were built during the 1980's and 1990's by various LIF programs, including KALIF, ETIGO, PROTO, GAMBLE, [5, 6, 7, 8] etc. For example, KALIF was based on a pulsed-forming line that can deliver 50 ns, 1.7 MV, 600 kA beam pulses. The generated proton beam could produce up to 1 TW/cm^2 of heating power on target. On the

other hand, KALIF-HELIA [9] has a pulsed-power generator based on an Inductive Voltage Adder (IVA) which produces 40 ns, 6 MV, 400 kA beam pulses (2.4 TW on target). The IVA structure provides an upgrade path to higher voltages and higher power.

Figure 1 shows a conceptual drawing of the NURA Single-Gap Accelerator based the KALIF-HELIA approach. It will deliver 30 ns, 2 MV, 500 kA proton beam pulses. If the beam can be focused down to a 1 cm diameter spot size, the power density on target will be 1 TW/cm² and the material can be heated to ~10 eV temperature. The voltage, current, pulse length, and repetition rate are not considered major difficulties in such a design. We believe that the most challenging task is generating a good quality beam from a carefully designed ion source, and a low aberration focusing system, such that the ion beam can be focused to a spot size small enough to meet the power density requirement.

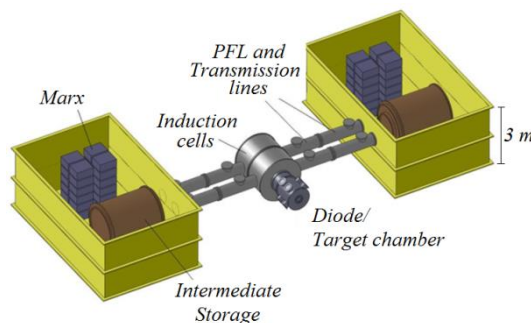


Fig. 1. NURA single-gap diode accelerator.

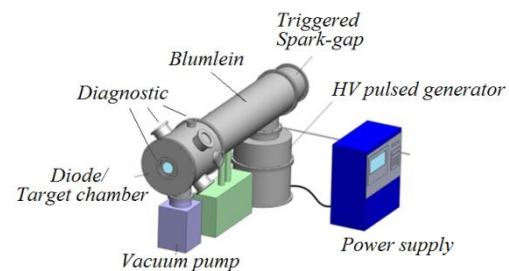


Fig. 2. A single-gap diode accelerator test stand.

3.2. A single-gap accelerator test stand is being constructed at NU

At present, NU, in collaboration with Tomsk Polytechnic University, is building a scaled version of the NURA single-gap diode accelerator. This pilot project is expected to be completed in one year. The test stand, as shown in Fig. 2, is designed to produce 10 kA of protons at 600 keV with a 30 ns pulse length. Beam power on target will be fractions of GW/cm² depending on the focal spot size (<5 cm). The test stand will be used to study beam transport and neutralization, for technical development of the NURA components including target diagnostics, and for other high intensity charged particle beam applications such as material modifications.

4. Neutralized beam transport experiment

A recent experiment was carried out at Tomsk Polytechnic University using the TEMP-4 single-gap accelerator to examine the effect of beam neutralization by a plasma. The accelerator produces 10 kA of proton beam in a conical shape with a kinetic energy of 370 keV and a pulse length of <100 ns [6]. Figure 3 shows the experimental layout.

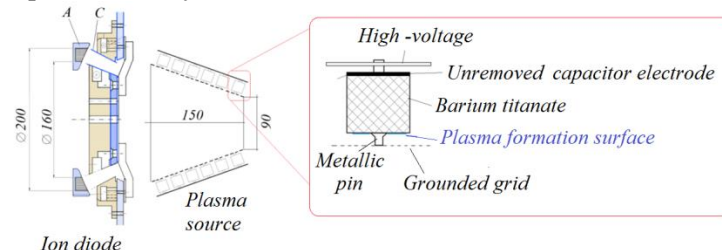


Fig. 3. Experiment layout of the Neutralized Transport Experiment.

In the standard configuration, the beam is neutralized by a background air pressure of $5 \cdot 10^{-4}$ - 10^{-3} Torr. In this experiment, the diode chamber was pumped down to below 10^{-5} Torr to minimize the presence of residual gas and a plasma was injected into the beam path before the beam arrival.

Figure 4 shows the conical ferroelectric plasma source that was built to generate plasma by flashover discharge. The plasma source is a hollow cone made of an array of barium titanate ceramic

capacitors with relative permittivity $\epsilon = 900 - 1000$. High voltage (17 kV, 4 μ s) is applied to the outer electrode and a grid on the inner surface connects all capacitors to ground. Flashover discharge, starting at the triple points of metal-ceramic-vacuum contact, is formed on the ceramic surface and the generated plasma flows through the grounded grid to fill the inner region of the conical plasma source.

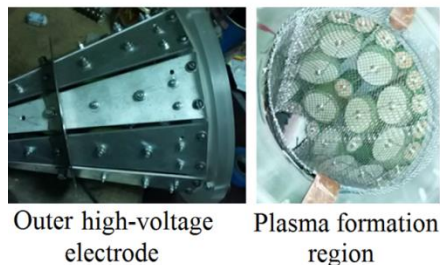


Fig. 4. Conical plasma source.

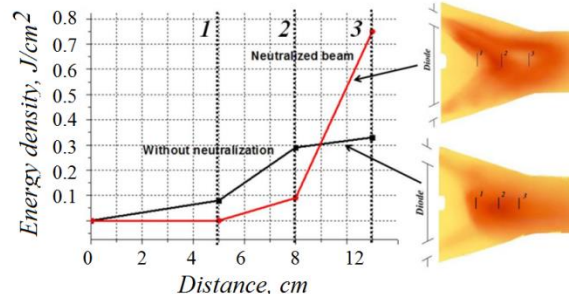


Fig. 5. Result of the Neutralized Transport Experiment.

By using a biased Faraday cup we estimated the plasma density to be $> 10^{10} \text{ cm}^{-3}$ near the grounded grid of the plasma source, where the beam is expected to be transported. A 1.5 cm diameter copper target was used as a calorimeter to measure the total energy of the ion beam at different distances from the cathode (5, 8, and 11 cm). The results showed that the ion beam had been neutralized, thus affecting the beam focus. The energy density of the ion beam at the focal spot increased by a factor of 2, with corresponding radiosensitive film confirming similar results as shown in Fig. 5.

5. Summary and conclusion

We have considered two options for NU to enter the field of High Energy Density Physics. An NDCX-type accelerator facility for WDM experiments, or a single-gap diode type accelerator that is more suitable for ICF-relevant hydrodynamic experiments. The second option can also be used for other high power beam pulse applications including electron beams. Within one year, a single-gap accelerator test-stand will be available for experiments at NU. In the mean time, we have started conducting beam neutralization experiments using the ion gun at Tomsk Polytechnic University.

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