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**Design and Fabrication of the Lithium Beam Ion Injector for
NDCX-II**

by

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DESIGN AND FABRICATION OF THE LITHIUM BEAM ION INJECTOR FOR NDCX-II

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Abstract

A 130 keV injector is developed for the NDCX-II facility. It consists of a 10.9 cm diameter lithium doped alumina-silicate ion source heated to ~ 1300 °C and 3 electrodes. Other components include a segmented Rogowski coil for current and beam position monitoring, a gate valve, pumping ports, a focusing solenoid, a steering coil and space for inspection and maintenance access. Significant design challenges including managing the 3-4 kW of power dissipation from the source heater, temperature uniformity across the emitter surface, quick access for frequent ion source replacement, mechanical alignment with tight tolerance, and structural stabilization of the cantilevered 27" OD graded HV ceramic column. The injector fabrication is scheduled to complete by May 2011, and assembly and installation is scheduled to complete by the beginning of July.

INTRODUCTION

The Neutralized Drift Compression eXperiment (NDCX-II) is for the study of high energy density physics and inertial fusion energy research utilizing a lithium ion (Li+) beam with a current of 93 mA and a pulse length of 500 ns (compressed to 1 ns at the target). The injector is one of the most complicated sections of the NDCX-II accelerator demanding significant design and fabrication resources. It needs to accommodate a relatively large ion source (10.9 cm), a high heat load (3-4 kW) and specific beam optics developed from the physics model [1]. Some specific design challenges are noted in this paper.

COMPONENTS

The injector consists of several subassemblies and components; including an ion source assembly, beam optics, beam diagnostics, solenoid with corrector coil, graded column, vacuum pumping, 6-strut support, pulsed power tank, source heater filament isolation transformer, cooling water grading base and linear rail and grounded safety cage.

Source Assembly

The ion source assembly consists of a molybdenum frame, tungsten heater filament with lug and bolt electrical connections, five layers of molybdenum-rhenium heat shield, and a 80% dense tungsten substrate on the front face of which a coating of lithium doped alumina-silicate is applied. The ion source surface is

heated to ~ 1300 °C to produce 1 mA/cm² of Li+ ion beam upon extraction. Current estimates of power required to heat the source are from 3-4 kW.

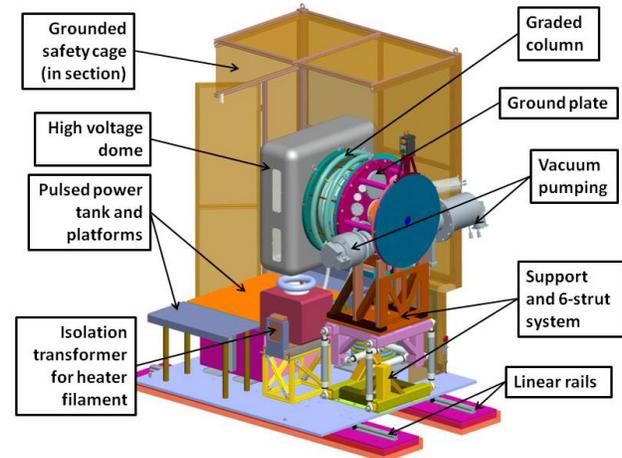


Figure 1: NDCX-II injector overall view and external components.

Fabrication of the source assembly is a specialty item that has a long lead time mostly due to the long lead in procuring the refractory metals needed for its construction and the multiple steps required in fabricating the powder processed tungsten substrate. In addition to this, the source is useful early in the assembly process so that experimental work can be done on the actual substrate to finish defining the coating and stripping procedure.

Beam Optics and Diagnostics

Beam optics consists of a three-electrode assembly and a ground plane, all of which are water cooled with low conductivity water. The Pierce (source) electrode is pulsed to +130 kV, the extractor electrode is pulsed to +117 kV and the accelerator electrode is at +20 kV DC. The Pierce and the source are mounted to a support structure that is attached to the high voltage plate via a 6-strut system for ease and freedom of alignment. The extractor is mounted to the high voltage plate via three alumina standoffs with field shaping "flowerpots" to protect the triple point. The accelerator electrode is mounted to the ground plate with identical standoffs.

Fabrication of the beam optics requires special attention to the machining precision and vacuum tight welding. All three electrodes are water cooled and are in a vacuum environment. The cooling channels are designed to withstand up to 150 psi. Also, since the welding process will warp the material, it is necessary to stress relieve the weld joints prior to the final machine work. These

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requirements make the optics some of the most expensive and long lead fabrications in the injector.

Injector beam diagnostics consist of a segmented Rogowski coil for diagnosing beam current and position. The location of the coil is immediately downstream of the ground plate and upstream of the gate valve and solenoid.

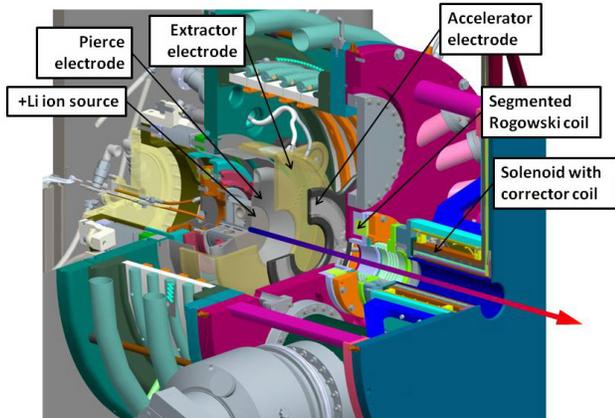


Figure 2: NDCX-II injector quarter cross section with beam optics components.

Solenoid

The solenoid design is the same as that used in the diagnostics intercells further downstream in the accelerator. A copper shield is used to confine the solenoid's magnetic field so that it doesn't saturate the ferrite cores in neighbouring induction cells. Likewise, the copper shield minimizes the magnetic field at the ion source, thus eliminates the need for a bucking coil.

Graded Column

A graded ceramic column separates the HV plate from the ground plate. An existing high voltage column was modified for this purpose. Tests have shown the column to be more than adequate for the pulsed voltage differential of 130 kV and the column has the correct ID to house the injector optics in this re-entrant design. This design also necessitates that the beam optics be mounted from the flanges at the end of the column. Some specific design issues occurred and are detailed below in the design challenges section.

Vacuum Pumping

There are three 10-inch ConFlat vacuum flanges, dedicated to vacuum pumping. These flanges are located on the ground plate which is upstream of the injector gate valve that isolates the injector volume from the rest of the accelerator. The isolation of the injector volume allows the injector to stay at atmospheric pressure while keeping the rest of the accelerator at vacuum. This is of particular importance in the case of NDCX-II because of the frequent ion source replacements expected. Currently, only two pumps are expected to be needed. A turbo pump and a cryopump will be mounted to these ports via 90° elbows.

Base Plate

The injector assembly is mounted at the ground plate to a support weldment that in turn mounts to a 6-strut support for alignment to the rest of the accelerator. The 6-strut system is mounted to a base plate which also has mounted to it the isolation transformer for the heater filament, a column for grading the cooling water, the pulsed power tank, operator platforms and the grounded safety cage. The base plate mounts to the ground via linear rails. These rails facilitate moving the entire injector assembly 2.5 feet away from the accelerator for the temporary installation of beam diagnostics immediately downstream of the injector or 1 foot closer in the event an accelerator reconfiguration occurs.

DESIGN CHALLENGES

Design challenges included managing a significant heat load, precisely aligning components along the beam line, accommodating frequent source replacement and evenly heating the surface of the source.

Heat Load

The heating element is expected to draw 3-4 kW of power. In this case, the major concern with such a high heat load is heating of the graded column which is made up of glued segments. The injector is designed so that there is no line of sight directly from the source or any heated part of the source assembly to the column in order to eliminate direct radiative heat transfer. Baffles are created by designing the extractor with a rim and installing a heat shield off of the HV plate, while still allowing generous conduction for vacuum pumping. Additionally, there are seven cooling water channels which will have LCW circulated through them to remove heat (Figure 3).

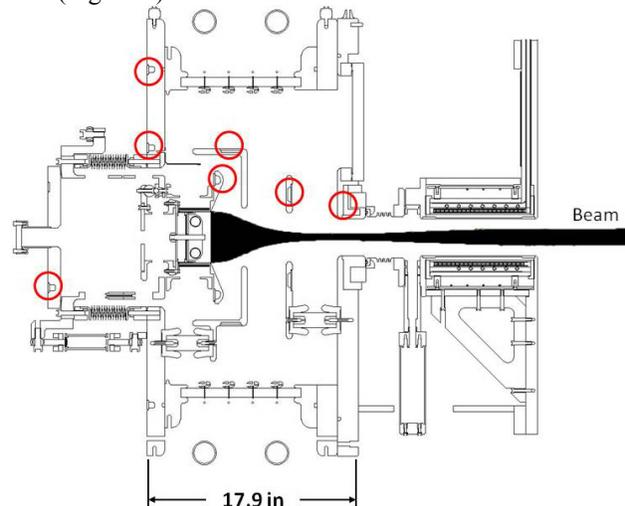


Figure 3: NDCX-II injector schematic with water channels circled in red.

With the shielding and water cooling in place, thermal calculations predict the maximum column temperature to be 47° C while the ion source surface is at 1300 °C. This is well below the temperature where the epoxy loses

strength. Nevertheless, the effects of elevating temperature on outgassing rates need to be taken into consideration. Samples of the epoxy were made and tested. The results show an elevated outgassing rate (Figure 4); however this is predicted to be well within the capacity of the vacuum pumps.

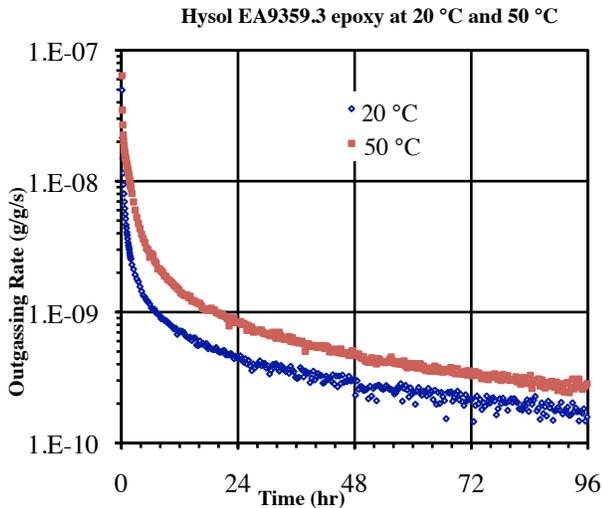


Figure 4: Epoxy outgassing rate test results for 20 °C and 50 °C.

Alignment

The alignment of components, specifically the beam optics, is a priority in the construction of the NDCX-II injector. The elements to align consist of the ion source, the Pierce electrode, the extractor electrode, the accelerator electrode, the ground plane beam pipe and the solenoid. The primary alignment strategy for the injector relies on precision measurement while assembling and then pinning parts together for repeatable positioning. The datum for the Z-axis (along the beam line) is the beam tube bore and ground plane (concentric to the bore and perpendicular to the ground plane). Offsets in the Z-axis will be determined with precision machining as will angular positioning about X and Y. Offset along the X and Y axis will be made by measuring the accelerator and extractor electrode internal diameters relative to the beam tube bore on the ground plate and then pinning the components in place. The Pierce electrode and source are mounted via a 6-strut support and are thus adjustable to the beam axis. The solenoid is adjustable in offsets in X and Y and in tilt and will follow a process developed for the NDCX-II induction cells [2].

Frequent source replacement

The relatively short life time of ion emission will require source replacement as frequently as every two weeks if the facility is in full-time daily operation. The injector has two full source assemblies and an extra substrate. The plan is that one assembly would be in use in the injector, with another spare unit ready to be installed, while the extra substrate is in process of being coated. Thus, the three substrates would be cycled through the injector and between the two assemblies. The

high voltage dome has two doors allowing access to the source access flange to facilitate easy source replacement of the source assembly which is mounts with a kinematic connection, insuring a repeatable position.

Even heating of the source surface

An even temperature distribution on the surface of the source is made difficult due to the large size of the source and the 80% density of the tungsten source substrate, but is important due to the limited lifespan of the alumina-silicate lithium ion source being, among other things, temperature dependant [3].

The source assembly and source surface temperature distribution was calculated in ANSYS as an axi-symmetric geometry (Figure 5). The tungsten filament which is a toroidal helix is represented in the calculation as 28 individual toroids arranged to represent the filament density distribution seen in the actual winding.

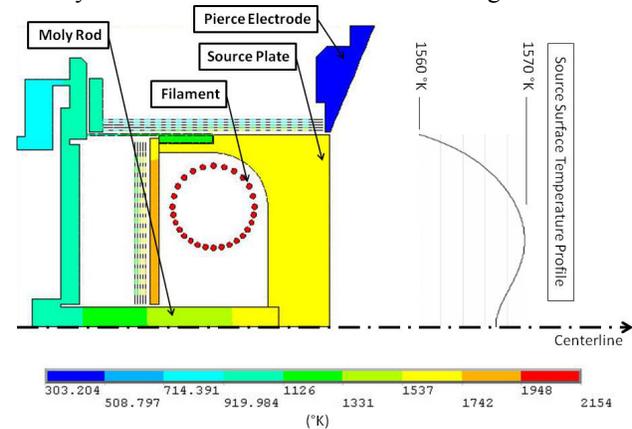


Figure 5: NDCX-II source temperature distribution on the source assembly components and the source surface temperature.

The calculation involves thermal conduction, convection and radiation. A heat density is applied on the area of filament to generate the required source surface temperature. Each material has thermal conductivity and emissivity for conduction and radiation. The filament location, the source plate thickness and the size of the molybdenum (moly) rod, which acts as a heat sink, were varied to minimize the temperature variation across the source surface to 9.5 °C. The maximum temperature is predicted to be 1296.5 °C and located at $r = 0.025$ m.

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