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### Authors

Sangster, T.C.

Ahle, L.E.

Halaxa, E.F.

et al.

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## A New 500-kV Ion Source Test Stand for HIF\*

T. C. Sangster, L. E. Ahle, E. F. Halaxa, V. P. Karpenko, M. E. Oldaker  
and J. W. Mitchell

Lawrence Livermore National Laboratory, Livermore, CA 94550

D. N. Beck, F. M. Bieniosek, E. Henestroza and J. W. Kwan  
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

### Abstract

One of the most challenging aspects of ion beam driven inertial fusion energy is the reliable and efficient generation of low emittance, high current ion beams. The primary ion source requirements include a rise time of order 1- $\mu$ sec, a pulse width of at least 20- $\mu$ sec, a flattop ripple of less than 0.1% and a repetition rate of at least 5-Hz. Naturally, at such a repetition rate, the duty cycle of the source must be greater than  $10^8$  pulses. Although these specifications do not appear to exceed the state-of-the-art for pulsed power, considerable effort remains to develop a suitable high current ion source. Therefore, we are constructing a 500-kV test stand specifically for studying various ion source concepts including surface, plasma and metal vapor arcs. This paper will describe the test stand design specifications as well as the details of the various subsystems and components.

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**Contact** T. Craig Sangster  
LLNL, P.O. Box 808, L-481  
Livermore, CA 94550  
Phone: 925-422-8176, Fax: 925-423-6319  
E-mail: [sangster1@llnl.gov](mailto:sangster1@llnl.gov)

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## **Introduction**

The leading candidate driver for inertial fusion energy (IFE) is a linear induction accelerator. This accelerator must deliver multiple heavy ion beams of unprecedented brightness to a spot only a few millimeters in diameter at a repetition rate between 5 and 10 Hz [1]. The appeal of an ion beam driver is fairly obvious – many decades of accelerator development driven by High Energy and Nuclear Physics needs have demonstrated that an IFE driver-scale machine combining high efficiency, durability, reliability and repetition rate should be feasible. The challenge will be to create and then accelerate ion beams at the space charge transport limit; this limit is many orders of magnitude beyond the state-of-the-art of present RF-driven High Energy and Nuclear Physics accelerators. Indeed, this is one of the primary goals of the Virtual National Laboratory for Heavy Ion Fusion (VNL-HIF) [2]. While state-of-the-art induction accelerator technology appears to be adequate to accelerate ion beams for IFE, it is not at all clear how these beams will be created. Furthermore, a technical solution for the generation of IFE driver scale beams must be developed before the Integrated Research Experiment (IRE) Conceptual Design Report (CDR) can be written.

The working specifications for an IFE driver ion source injector (output beam is matched to a magnetic transport lattice) are summarized in Table 1. Although cost and

scale are difficult to quantify for a working specification, they are clearly important design and feasibility issues. The required current density will depend significantly on the technique used to create the beams. For example, a source in which small beamlets are merged into a single one ampere beam will require current densities approaching 100 mA/cm<sup>2</sup>; a single large surface emitter may only produce 10 to 20 mA/cm<sup>2</sup> yet still generate a beam of suitable current and radius. The emittance limit is presently not well determined and based on beam dynamics simulations that suggest that the emittance growth during acceleration combined with such a limit on the ion source and injector would allow the beam to be compressed and focused onto a target. The remaining specifications are derived from IFE system studies that suggest an optimized ion source injector would provide multiple matched beams at about one ampere with a high duty cycle, high repetition rate and an initial pulse duration of approximately 20-μsec.

Existing ion sources and ion source test facilities have fallen far short of meeting these specifications. In most cases, existing ion sources have produced low current density beams from space charge emission limited surface emitters for scaled beam dynamics experiments. The existing 2-MeV injector at LBNL, the expected ion source for the Phase I High Current Experiment (HCX), was not designed for ion source development. Therefore, the VNL-HIF is developing an ion source test stand to address, in aggregate, most of the technical issues associated with the specifications listed in Table 1. In particular, the pulsed power systems of the test stand are being designed for the

duty cycle, pulse duration and beam current specifications. The primary goal of the test stand, however, is to develop the technology to produce a suitable beam current density for the required beam pulse length. The design philosophy has been to maximize flexibility to accommodate the wide variety of potential ion source technologies (in other words, we do not want to exclude a promising technology due to design limitations of the test stand). These include surface emitters, RF-driven plasmas and metal vapor arcs. This paper will describe the design considerations and technical choices (and tradeoffs) that have been adopted to meet this goal. Once operational, a complete set of measurements (current density, emittance, stability, etc.) will be performed on every promising ion source concept to provide a consistent basis for the selection of an ion source technology for the IRE CDR.

### **Mechanical Design Considerations**

To ensure a high degree of operational flexibility, the accelerating or insulating column will be operated in air. Figure 1 shows a schematic layout of the ion source test stand mechanical structure. Despite being a vertical beam line, the layout of the test stand is fairly conventional. A high voltage pulse is delivered to a dome structure containing the ion source and a voltage divider is used to grade the accelerating potentials on a grid structure in an insulating column. A diagnostic tank at the bottom of the insulating column is then used to measure the properties of the created beam.

What is not so conventional is the degree of flexibility being incorporated into the design of the insulating column and the dome structure for the rapid installation of new ion sources and grid structures. Indeed, one of the primary design considerations for the test stand was that a new source could be installed within a matter of days. Since the ceiling height of the test stand laboratory is in excess of 30 feet and the laboratory is equipped with an overhead crane, ease of assembly and source installation issues combined with environmental and safety concerns led to the decision to build a vertical beam line. The high voltage (HV) deck is located approximately 16 feet above the floor with the source pointed toward the floor. The x-ray flux from back-streaming electrons is then toward the concrete ceiling and away from operating personnel.

To accommodate a broad range of source technologies, the insulating column consists of five identical sections (see Figure 2). The column can then be disassembled to accommodate a new accelerating grid structure and the grid structure aligned during column re-assembly. The end flanges, ceramic insulating rings (the  $\text{AlO}_2$  rings have a 27" OD, a wall thickness of 2" and were manufactured by CoorsTek ceramics [3]) and the corona flanges of each section will be glued together (using Dexter-Hysol XEA 9359.3) with a custom jig assembly. Brazing did not appear to be a cost effective alternative to gluing. After gluing, final machine work on the end flanges will ensure proper alignment of the assembled column. A conventional water resistor will be wound

around the column (nominally 8 turns) to provide voltages to the end flanges and corona rings for the accelerating grid structures inside the column.

The insulating column will bolt to a diagnostic tank that is directly supported from the floor. This tank will contain two orthogonal (“x” and “y”) parallel slit scanners for emittance measurements, a Faraday cup, a vacuum re-entrant diagnostic port, several viewing ports and a Gated Beam Imager [4]. At least one 16” cryogenic pump will be supported on the diagnostic tank (the expected vacuum at the source in the insulating column is  $10^{-7}$  torr) along with pump out ports and a full suite of vacuum gauges.

The HV dome at the top of the test stand (see Figure 1) will contain all of the components required to operate the source. Although some of the details of the dome structure are not yet complete, the dome structure itself will be supported directly from the floor using four insulating fiberglass legs. The insulating column and diagnostic tank will be supported separately from the floor. Therefore, only electrical connections will be made between the HV dome and the insulating column. To accommodate personnel access and work in the dome, a temporary scaffold structure is being designed. This scaffold will allow two people to work comfortably at the dome elevation but will be removed for energized operations. The turnaround time for the scaffold installation and removal is expected to be less than 2 hours. A second permanent scaffold structure will

be located at the base of the diagnostics tank (a few feet above the floor) to allow personnel to work comfortably at the diagnostics elevation.

### **Pulsed Power Design Considerations**

The specifications for the ion source pulser are listed in Table 2. The design philosophy was to emphasize simplicity and reliability to minimize construction and operating costs. Therefore, a PFN-pulse transformer concept was selected over a Marx power supply. As a compromise between development and component costs, beam dynamics and source performance, the maximum ion energy was fixed at 500-keV. At lower beam energies, the performance of an ion source could be obscured by space charge expansion before the beam reaches the diagnostics. At higher beam energies, voltage breakdown limits in air would require the insulating column to be operated in a secondary chamber containing SF<sub>6</sub> or pressurized CO<sub>2</sub> (for example), losing much of the desired operational flexibility. Furthermore, the performance specifications would necessarily approach those of an IFE driver and the cost to develop would become prohibitive for little or no additional developmental capability. Similarly, the repetition rate and voltage ripple specifications were fixed at 1-Hz and  $\pm 0.5\%$  RMS, respectively. Although these specifications are inadequate for an IFE driver, they again fall within an acceptable development cost envelope and will not affect the capability of the test stand to discriminate among various source options. The pulse width, on the other hand, was



chosen to be the nominal 20- $\mu$ sec from Table 1 so that driver relevant issues such as ion depletion, neutral ion emission, etc. could be realistically assessed.

Other issues affecting the design of the pulsed power system for the test stand include the resistive and capacitive load of the voltage divider and dome, floor space available and environmental and safety considerations for oil or SF<sub>6</sub> and stored energy. Figure 3 shows a schematic of the final pulser system design. A 6.5 ohm, 18-stage Raleigh type PFN, pre-charged to 100-kV, delivers a pulse through a standard peaking compensation circuit to a custom designed, inverting 1:12 transformer [5]. The compensation circuit greatly enhances the pulse rise time allowing the PFN to be reduced from 30 to 18 stages while still delivering an acceptable voltage ripple. A thyatron switch is used to trigger the pulser system. The primary inductance of the transformer should be 400 mH while the secondary inductance is expected to be 250  $\mu$ H. Using the standard model of transformers, the minimum expected rise time out of the transformer (with a leakage capacitance estimated to be 450 pF) is calculated to be about 550 nsec (the rise time delivered to the source is expected to be another 250 nsec slower due to the capacitance of the interconnections and the dome). The pulse transformer delivers a positive 500 kV pulse to the HV dome at the top of the test stand via a HV oil-to-air bushing. From the dome, a conventional water resistor (sodium thiosulphate) provides a return path to ground and the various voltages for the accelerating grid structure inside the column. An additional bifilar wound secondary winding on the transformer provides

20 A of 480 VAC inside the dome at the HV deck potential to operate the source and auxiliary equipment.

For several reasons, a crowbar circuit has not been designed into the initial implementation of the pulser system. Since the PFN behaves like a transmission line as it delivers energy, an arc that shorts the load will double the delivered current for the remainder of the pulse but, as the arc impedance is small, deposit only a modest amount of energy. Most of the energy will be reflected and then fully absorbed by a reverse diode in series with the 6.5-ohm resistor used to match the transmission characteristics of the PFN. Furthermore, due to the energy stored in the transformer, a crowbar could only reduce the initial energy deposited by 75%. Therefore, the additional cost of the crowbar circuit, estimated at over \$50k, was believed to be unwarranted.

The initial design of the PFN was for operation in air. By operating in air, the expectation was that the system would be easier to tune and maintain. Furthermore, operation in air avoided the need for a second oil tank (the main inverting transformer will be located in oil). However, field stress calculations on the PFN components in air indicated that at 100 kV, these stresses would be difficult to manage in a simple, reliable, cost effective manner. Therefore, the 18-stage PFN and the thyatron trigger will be located in a separate oil tank. A closed loop heat exchanger will be used to cool the oil in both tanks. Finally, to achieve a repetition rate of 1-Hz, the charging power supply must

provide 200-mA at 100-kV. Several commercial vendors offer suitable products with these specifications.

The pulser system will be assembled at Lawrence Livermore National Laboratory and is expected to be operational by the end of CY00. Figure 4 shows the expected output waveform using a model developed by one of the co-authors (MEO). The load parameters used were quite conservative. The expected pulse rise time is somewhat less than 900-ns, well within the specification listed in Table 2. Each of the PFN inductors can be individually tuned over a range of about 10-15% to ensure the proper flattop response.

### **Design and Fabrication Status**

Virtually all of the major components of the ion source test stand pulser system have been completely specified. Most of the components have been ordered. The final remaining task before the PFN assembly can begin is the design and fabrication of the PFN cabinet and oil tank. The design of the insulating column is nearly complete and gluing of the five sections will begin by early fall, 2000. The diagnostics tank has been designed and delivery is expected by late summer. The final design of the HV dome and support structure should be completed by late summer.

When operational at the end of CY00, the new VNL-HIF ion source test stand will be an invaluable tool for high current ion source

development. Initial tests will be performed using a large area surface emitter (likely a potassium zeolite). These tests will be followed by measurements of beamlets created by a RF-driven plasma source. Future plans also call for evaluating the properties of a metal vapor arc source.

## References

- 1) M. Tabak *et al.*, Nuclear Fusion **38** (4), 509 (1998); R. Moir, Proceedings of ICENES98, Tel Aviv, Israel, June 28-July 2, 1998 (to be published).
- 2) Participating institutions include LBNL, LLNL and PPPL.
- 3) CoorsTek structural ceramics, 16000 Table Mountain Pkwy, Golden, CO 80403.
- 4) L. E. Ahle and H. S. Hopkins, AIP Conference Proceedings **451**, 507 (1998).
- 5) The transformer is being manufactured by Stangenes Industries, Inc., 1052 East Meadow Circle, Palo Alto, CA 94303-4230

## Figure Captions

**Figure 1:** A schematic layout of the ion source test stand showing the HV dome above the insulating column on top of the diagnostics tank. The HV dome is supported separately from the column and diagnostics tank. Some of the mechanical support structure is not shown. Also missing are the transformer and PFN tanks.

**Figure 2:** A mid-plane section through the insulating column showing the five identical sections for ease of assembly and disassembly. The dimensions are in inches. Also shown is the relative location of the water resistor that loops around the column.

**Figure 3:** A detailed schematic of the 500 kV pulser system.

**Figure 4:** The calculated waveform delivered to the HV dome by the PFN-transformer circuit in Figure 3.

Table 1: The working specifications for an IFE driver ion source injector.

Source current density	$\sim 10\text{-}100 \text{ mA/cm}^2$
Number of beams	$\sim 100$
Current per beam	$\sim 1 \text{ A}$
Output beam radius	$\sim 1 \text{ cm}$
Ion Energy	1.6 MeV
Pulse duration	$\sim 20 \text{ }\mu\text{sec}$
Repetition rate	$\sim 10 \text{ Hz}$
Final emittance	1 mm-mr
Duty cycle	$> 10^8 \text{ pulses}$

Table 2: Specifications for the ion source pulser.

Voltage	$\sim 500\text{-kV}$
Pulse length	20- $\mu\text{sec}$
Rise time	$\sim 0.9\text{-}\mu\text{sec}$
Ripple	$\sim 0.5\%$
Resistive load	$\sim 850$
Capacitive load	$\sim 200\text{-}300 \text{ pF}$
Repetition rate	$\sim 1\text{-Hz}$
Maintenance cycle	$> 6 \text{ mo}$
Lifetime	$10^7 \text{ pulses}$