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

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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-μsec, a pulse width of at least 20-μsec, 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 arc. This paper will describe the test stand design specifications as well as the details of the various subsystems and components.

PACS codes 41.75Ak, 52.58.Hm, 52.50.Dg, 29.25.Ni

Keywords Heavy ion sources; Heavy ion fusion; Pulsed power; High voltage

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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, which 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.

The working specifications for an IFE driver ion source injector 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^2; a single large surface emitter may only produce 10 to 20 mA/cm^2 yet still generate a beam of suitable current and radius. The emittance limit is somewhat arbitrary and based on preliminary 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. These specifications are, in aggregate, beyond the VNL-HIF state-of-the-art.

Therefore, the VNL-HIF is developing an ion source test stand to address, in aggregate, many 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. 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.

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 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_6 or pressurized CO_2 (for exmple), 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 ±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-μsec from Table 1 so that driver relevant issues such as ion depletion, neutral currents, 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_6 and stored energy. Figure 2 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 Gibbs compensating circuit [5] to a custom designed, inverting 1:12 transformer [6]. The Gibbs 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 thyratron switch is used to trigger the pulser system. 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 thyratron 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 FY00. Figure 3 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 risetime is somewhat less than 900-ns, well within the specification listed in Table 2.

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 Spring, 2000. The diagnostics tank has been designed and delivery is expected by mid-Spring. The final design of the HV dome and support structure should be completed by mid-Spring.

When operational at the end of FY00, the new VNL-HIF ion source test stand will be an invaluable tool for high current source development. Initial tests will be performed using a large area surface emitter. These tests will be followed by measurements of beamlets created by an RF-driven plasma source. Future plans also call for evaluating the properties of a metal vapor arc source.

References

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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) Gibbs circuit, TBD.
6) 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 dis-assembly. 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	~ 10-100 mA/cm^2
Number of beams	~ 100
Current per beam	~ 1 A
Output beam radius	~ 1 cm
Ion Energy	1.6 MeV
Pulse duration	~ 20 μsec
Repetition rate	~ 10 Hz
Final emittance	1 mm-mr
Duty cycle	> 10^8 pulses

Table 2: Specifications for the ion source pulser.

Voltage	~ 500-kV
Pulse length	20-μsec
Rise time	~ 850-μsec
Ripple	~ 0.5%
Resistive load	~ 850 Ω
Capacitive load	~ 200-300 pF
Repetition rate	~ 1-Hz
Maintenance cycle	> 6 mo
Lifetime	10^7 pulses

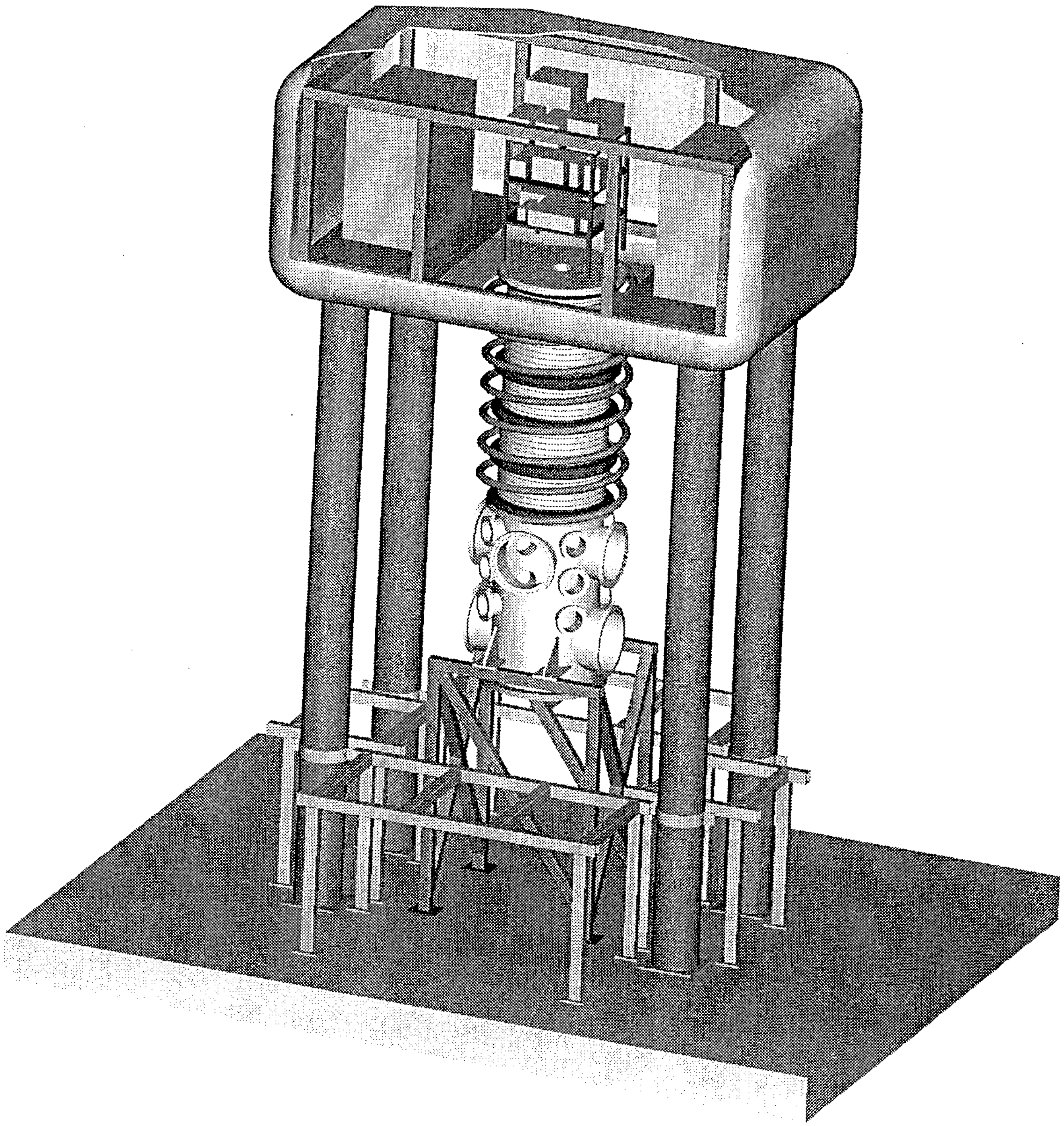


Figure 1

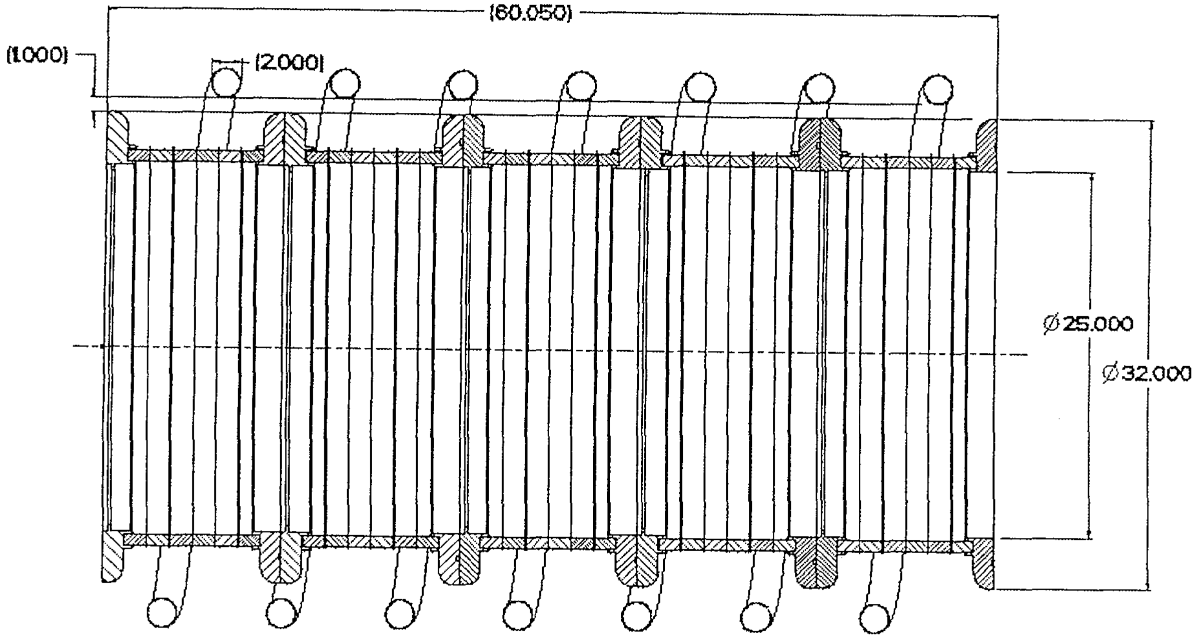
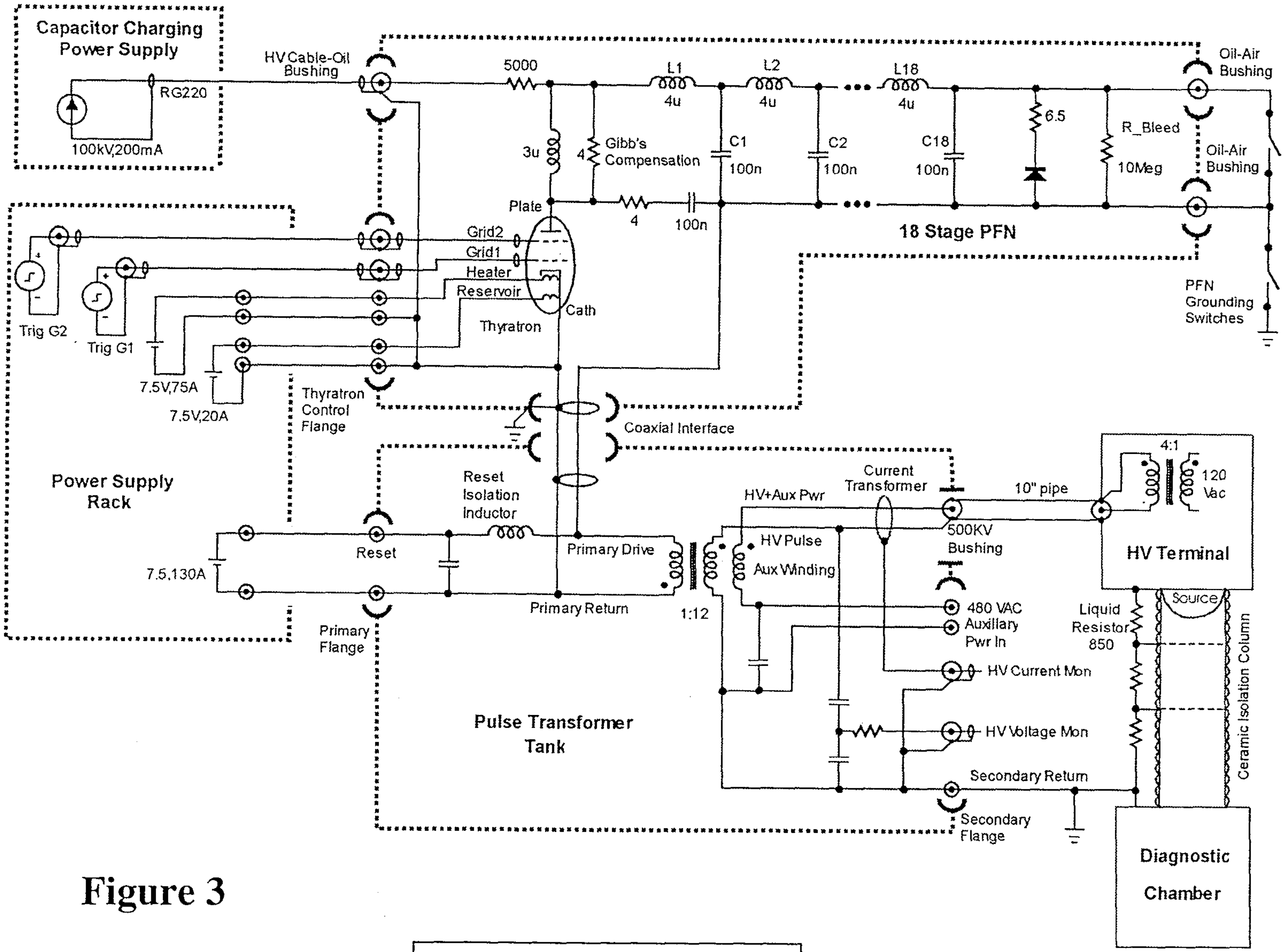


Figure 2



Capacitor Charging Power Supply
RG220
100kV,200mA
HV Cable-Oil Bushing
5000
L1
4u
L2
4u
L18
4u
Oil-Air Bushing
3u
4
Gibb's Compensation
C1
100n
C2
100n
C18
100n
6.5
R_Bleed
10Meg
Oil-Air Bushing
Plate
4
100n
18 Stage PFN
Grid2
Grid1
Heater
Reservoir
Cath
Thyratron
Trig G2
Trig G1
7.5V,75A
7.5V,20A
Thyratron Control Flange
PFN Grounding Switches
Coaxial Interface
Power Supply Rack
Reset Isolation Inductor
Reset
Primary Drive
7.5,130A
Primary Return
Primary Flange
1:12
HV+Aux Pwr
HV Pulse
Aux Winding
Current Transformer
500KV Bushing
10" pipe
4:1
120 Vac
HV Terminal
480 VAC Auxiliary Pwr In
HV Current Mon
HV Voltage Mon
Secondary Return
Secondary Flange
Liquid Resistor 850
Source
Ceramic Isolation Column
Pulse Transformer Tank
Diagnostic Chamber

Figure 3

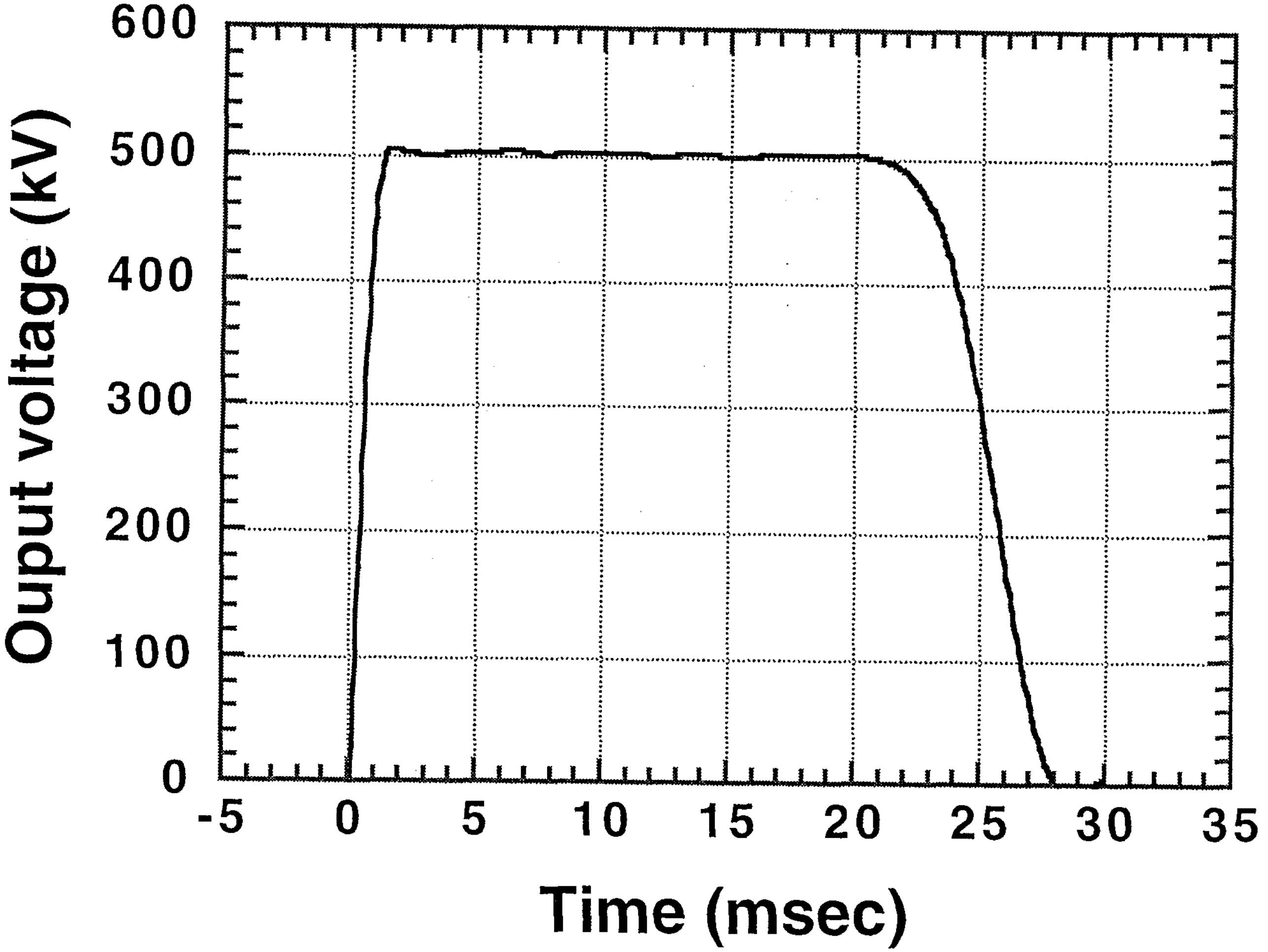

600
500
400
300
200
100
0
-5
0
5
10
15
20
25
30
35
Ouput voltage (kV)
Time (msec)

Figure 4