A HIGH INTENSITY 1.5 MEGAVOLT HEAVY ION
PREACCELERATOR FOR ION BEAM FUSION*

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Abstract

A preaccelerator is being developed at Argonne National Laboratory (ANL) in a program to demonstrate the accelerator technology which will be needed for power plants utilizing inertial-confinement fusion (ICF). The preaccelerator has been constructed and is now undergoing performance tests with the initial objective of achieving pulsed 30 mA beams of 1.5 MeV Xe^{+1}. The design, construction, and initial performance of the preaccelerator are described.

Introduction

System designs for commercial power plants utilizing inertial-confinement fusion driven by heavy-ion accelerator systems are showing excellent progress. The most promising design concepts incorporate a full energy linac to fill multiple storage rings with greater than 1 Megajoule of beam energy which must be extracted on to a deuterium-tritium pellet in a 10 nanosecond pulse. Projects to demonstrate the accelerator technology necessary for ICF power plants are scheduled to begin in the next two years. The experimental work described here is part of the Ion Beam Fusion (IBF) program at Argonne National Laboratory (ANL) where the first conceptual design for an accelerator driver for ICF was developed in 1976.[1] Our modest experimental program of the past one and one-half years is an effort to develop an appropriate injector for an ICF accelerator. The requirements for the injector are essentially the same for all of the conceptual accelerator designs: 100 µs pulsed 25 mA beams of heavy ions (A > 100) at ∿ 20 MeV with a normalized transverse emittance, $E_n \le 0.03$ cm-mrad. At 20 MeV the ions will be stripped to a higher charge state for more efficient acceleration. The most convenient ion to use is Xe^{+1} from the standpoint of ion source and accelerating column construction and reliability. This would then be stripped to Xe^{+8} at 20 MeV with approximately a 25 per cent efficiency. It would be accelerated to full energy in this minimum cross section charge state.

An IBF injector would be composed of a "tree" of two separate beam lines which are combined after stripping for injection into a single linac. Each branch will contain a preaccelerator followed by a low-beta RF linac operating at 12.5 MHz. The Xe^{+1} beam exits the low-beta linac at a kinetic energy of 20 MeV and enters a gas stripper section after which the Xe^{+8} component of the beam is deflected into a 25 MHz RF linac with the phasing such that alternate bunches are filled by alternate branches of the injector. Double-harmonic bunchers will be employed prior to both linacs to maximize their current acceptance.

The large space charge forces of such high current beams imposes unacceptably small current limits on the low-beta linac for low energies (< 800 keV) and low focussing power between accelerating gaps. For

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instance, the current limit for 750 keV Xe^{+1} of a $\pi/5\pi$ structure with magnetic quadrupoles between drift tubes of gradient 40 T/m is approximately 20 mA. This can be doubled by injecting at 1.5 MeV and by using superconducting quadrupoles with gradients greater than 100 T/m. With the higher magnetic focussing, the structures can also be made shorter by using a $\pi/3\pi$ geometry. Another advantage of high preaccelerator voltage which may be more important than the current limit is the higher starting frequency of the linac. Each frequency jump in the linac will introduce beam loss and transverse emittance dilution. Additional transitions below 12.5 MHz may lead to an unacceptably large number of branches to the "tree" just to get the desired current and emittance after large beam losses in those sections.

A commitment to developing the highest possible preaccelerator voltage was made at the beginning of our R & D program. After one and one-half years the preaccelerator is completed and is nearing its operating goal of 1.5 MeV. The initial section of low-beta linac is being tested and will be installed with conventional magnets with gradients of 46 T/m; however, the ANL superconducting group has a very promising test magnet for the linac which should operate above 100 T/m.

High Voltage Power Supply

The high voltage power supply is a modified Radiation Dynamics, Inc. (RDI) 4 MeV Dynamitron[2] which had been surplussed by the Goddard Space Flight Center. This is a parallel-fed capacitively-coupled voltage multiplier driven by a 110 kW oscillator operating at 105 kHz. We have made extensive modifications to increase the current capability and allow pulsed operation. A new solid-state rectifier stack was installed with two 40-rectifier circuits in a full-wave configuration. With adequate oscillator power, the stack could support 100 mA at 2 MV. The RF electrodes-stack spacing was decreased from 46 cm to 30 cm to improve the capacitive coupling and new rigid electrode supports were installed to prevent large mechanical resonances during pulsed operation. The rectifier stack and RF electrodes are shown in Fig. 1. We also decreased the turns ratio of the RF toroidal transformer from 31.3/1 to 24/1 to optimize operation at 1.5 MV. This lowered the terminal impedance by 40 per cent and left adequate plate voltage to support beam current at 1.5 MV. Other mechanical modifications were made such as lengthening the pressure vessel 92 cm and adding a quick-opening flange at the end where the new accelerating column is located (in the original configuration the low-gradient column was inside the rectifier stack with the beam exiting the end at the base of the stack).

We have extensively tested the capability of this power supply in pulsed and dc operation. This type of accelerator had never before been pulsed. The power oscillator was unchanged from RDI's design except for the addition of a new pulse programmer. Extensive diagnostics were incorporated for remote readout of virtually all oscillator and resonant tank parameters. A variable conductivity chilled-water resistor was installed between the terminal and ground so loading effects could be measured. The oscillator could ramp the terminal from 0.5 MV to 1.5 MV in 7 ms with measured peak stack currents of 70 mA. It was capable of 30 mA of dc current at 1.5 MV. The power

supply resonant Q was measured to vary from 500 un-
loaded to nearly 100 with a 50 mA load. The power
supply easily supported 2 MV operation when pressurized
with 65 psig of SF_6.
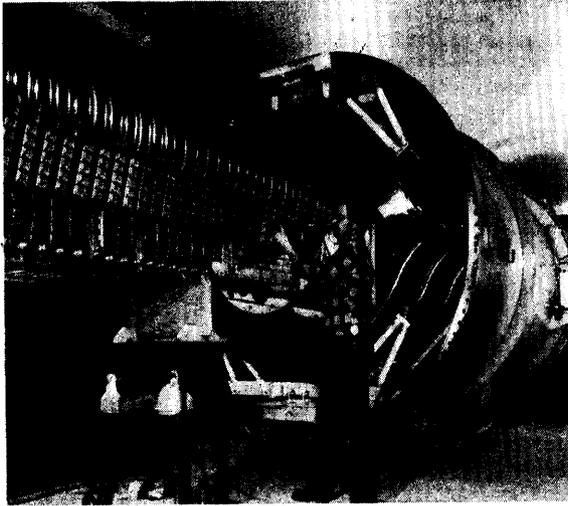
Fig. 1 The rectifier stack and terminal during instal-
lation. The RF electrodes are visible in the
pressure vessel to the right.

The Dynamitron power supply performs very well for
pulsed duty up to 2 MV and probably higher. With the
new terminal and column the total capacitance is
approximately 500 pF, so the damage from a spark is
minimal. During 100 µs beam pulses the oscillator will
be ramped to minimize voltage droop. At 1.5 MV the
voltage droop will be less than 0.25% for 42 mA of
beam associated current. This capability can easily be
doubled by adding a second pass tube with energy stor-
age in parallel with the original oscillator pass tube.

Heavy Ion Source

The low-emittance heavy ion source for our pre-
accelerator was developed under contract by Hughes
Research Laboratories (HRL) and is described in detail
elsewhere in this conference.[3] It is a scaled-up ver-
sion of their very successful 2 mA single aperture
source whose performance is also described at this
conference.[4] These utilize a Penning discharge for low
plasma temperatures and a Pierce extraction for minimal
emittance dilution during acceleration. Any vaporized
element can be accelerated by these sources; however,
Xe is the least problematic of the heavy elements. A
mercury vaporizer similar to those used by HRL in their
ion thrusters for space propulsion has been used suc-
cessfully in source tests, but its practicability needs
demonstrating. An accelerating column would have to be
developed which could avoid contamination of the elec-
trode and insulator surfaces with condensed mercury.
These uncertainties and the safety aspects of mercury
eliminate it from consideration in our present program.

The ion source has a divergent solenoidal magnetic
field which is produced by permanent bar magnets ar-
ranged outside the anode. The filament (cathode) is on
continuously, but the gas valve and anode are pulsed.
In typical operation the gas valve is opened for 5 ms
and then 30 ms later the anode is pulsed for 100 µs.
The current extracted is a function of the electric
field of the first gap of the accelerating column. The
source and column are designed to handle up to 100 mA
of Xe^{+1} with a current density of 15 mA/cm^2.

The ion source has been tested at HRL to currents
of 100 mA into a low voltage and 30 mA at an extraction
voltage of 100 kV. No problems of sheath instability
across the 3 cm aperture were encountered and the Xe^{+1}
component was measured to be greater than 90%. Emit-
tance measurements will be made in our beam line. The
normalized transverse emittance is expected to be less
than 0.01 cm mrad. The source turns on in less than
10 µs, but it requires more than 100 µs to shut down.
Development work will continue on reducing this transi-
tion time to minimize the time that beam is spraying
the column from being overfocussed at low current
densities.

The source timing pulses are transmitted to the
terminal via two Augat fiberoptic data links capable of
10 Mb/s. At present the voltages of the terminal power
supplies are adjusted by control rods. These will soon
be replaced and full monitoring capability installed
via additional fiberoptic links.

Accelerating Column

The high-gradient accelerating column is illus-
trated in Fig. 2. The ion source is re-entrant into
the terminal end and the ground electrode which is also
re-entrant houses a magnetic quadrupole triplet to focus
the beam on the linac buncher gap. The outer shell of
the column is 117 cm long and consists of 30 ceramic
rings and titanium discs which are epoxy bonded. An
indium O-ring isolates the bond from the internal vac-
uum. A voltage stress relief gap was ground into the
ceramic rings on the inner radius at the metal-insulator
joint. The ceramic wall is protected from ion bombard-
ment and sputtering by interlocking T-shaped rings.
The bottoms of the "T's" concentrate the field at the
center of the gap, thereby reducing the field gradient
at the metal ceramic joint to a minimum. The average
wall field gradient is 15 kV/cm.
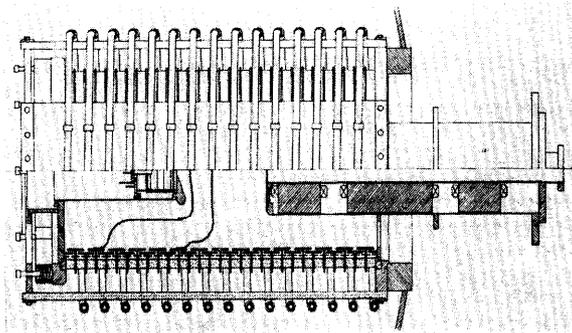
Fig. 2 The 1.5 MeV accelerating column with re-
entrant source and focussing quadrupoles.

The optics of the column are designed to handle up
to 100 mA of Xe^{+1} to 1.5 MeV with a current density of
15 mA/cm^2. The acceleration occurs within 34 cm with a
peak axial electric field of 60 kV/cm. The acceler-
ation up to the second intermediate electrode (650 kV)
is a Pierce geometry and is followed by a constant
gradient region. The final beam diameter is expected
to be 3.2 cm with a divergence half-angle of 23 mrad.
For a 30 mA Xe^{+1} beam, the intermediate electrodes re-
main in the same position, but are operated at 100 kV
and 468 kV. For this case the beam should be slightly
convergent with a final diameter of 1.2 cm. The accel-
erating gradients are 51 kV/cm in the Pierce region and

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49 kV/cm in the linear region.

The voltage divider string which spirals down the outside of the column consists of 60 Carborundum ceramic resistors with a total of 300 MΩ impedance. This is mounted on the plexiglas column support plates as shown in Fig. 3. A current drain of 5 mA down the divider string at 1.5 MV should be adequate to prevent large imbalances in the gradient during beam bursts.
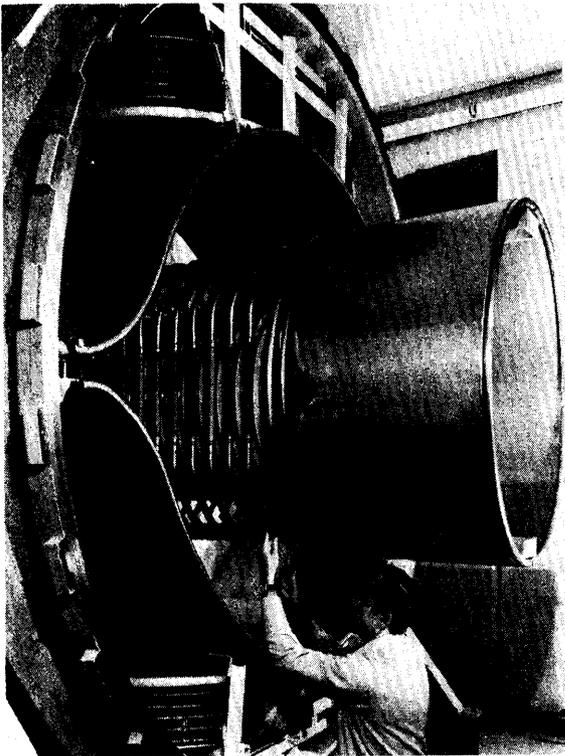
Fig. 3 The accelerating column with resistor divider and source section of terminal. Cooling units are above and below high voltage shields.

The ground end magnetic quadrupole triplet is inserted in the ground electrode through the vacuum manifold at the end of the preaccelerator. It is 90 cm long and has an outer diameter of 29 cm and a bore diameter of 10 cm. The peak field gradient is 20 T/m with pole tip fields of 1.0 T. The high conductance manifold is pumped by five Ultek 1000 ℓ/s cryopumps. The column is therefore susceptible to hydrocarbon contamination only during the short periods when a mechanical pump is used to establish a rough vacuum. The ultimate vacuum of the column is 1 x 10^{-7} mmHg. With a pulse repetition rate of 1 Hz the gas load of the source will raise this to 1 x 10^{-6} mmHg. The pumping manifold can be seen in Fig. 4 at the downstream end of the preaccelerator.

Status

The assembly of the preaccelerator was completed in mid-February and initial tests started. The first objective is to condition the column to 1 MV and study its operation with a 30 mA Xe^{+1} beam. Then it will be conditioned as high as possible and Xe^{+1} beam extracted at 1.5 MeV. So far the column has been conditioned to 900 kV, this required only 10 hours and very few sparks. However, the conditioning had to be terminated because of failures of the resistors in the divider string.

Alternate resistors will soon be available and our testing will resume. The beam diagnostics necessary for tuning the transported beam are being installed.[5] As soon as the beam is optimized at 1.5 MeV, it will be transported through the linac buncher and first cavity.[6]

Fig. 4 The accelerating column pumping manifold and beam port of preaccelerator.

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