OPERATION AND STATUS OF THE ANL HEAVY ION FUSION LINAC*

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Summary

The primary goal of the experimental program in heavy ion fusion (HIF) at Argonne National Laboratory (ANL) is to demonstrate many of the requirements of a rf linac driver for inertial confinement fusion. During the past three years, most of the construction effort has been applied to the front end. So far, the preaccelerator and first three linac cavities are operational with 20 mA Xe^+ beams at 2.2 MeV. The performance of the front end is discussed. The development of an electroplating technique and its use in the Wideroe linacs to reduce the construction costs is described. The future plans and options for the test bed are also presented.

Introduction

When the ANL program was started there were many uncertainties about how to develop an adequate linac for the rf linac/storage ring approach to HIF. Most of these involved the front end: bright 50 mA heavy ion sources did not exist, the low current limits of linac structures required the development of very high voltage preaccelerators, and the control of emittance growth in the linac structures was uncertain. The RFQ was an interesting, but untested concept.

We started the development of a high current heavy ion front end for two reasons: first, to demonstrate that it was possible and had good long-term reliability; and second, to provide intense beams for a rf linac/storage ring test bed. The initial test bed linac would accelerate more than 40 mA of Xe^{+8} to 220 MeV.

At this point, we have demonstrated many of the requirements of the front end. A very bright single-aperture Penning discharge source capable of 100 mA of Xe^+ was developed. A 1.5 MV preaccelerator was constructed and operated with 40 mA beam currents. A buncher and three linac cavities have accelerated 20 mA currents to 2.2 MeV. Fast, non-destructive beam diagnostics were built and operated to tune and analyze the beam. With the projected reduced budgets, the continued construction of a test bed is not possible. Of course, there are always new ideas and developments that should be pursued. Also, the long-term reliability of a facility requires extended operation. Scaled-down program options are now being considered which effectively utilize what has been developed and which address the most pressing uncertainties in the HIF scenarios.

Ion Source and Preaccelerator

A 100 mA low-emittance xenon (and mercury) ion source was developed for this program by Hughes Research Laboratories.[1] It is a Penning discharge, Pierce extraction source with a single 3 cm diameter aperture. Xe^+ currents of 100 mA have been extracted with no indication of plasma sheath instability. For typical operation at 40 mA, the aperture in the focus electrode is reduced to 2.1 cm diameter to increase the current density to 12 mA/cm^2 and to reduce the gas load in the accelerating column. The voltages and timings of the pulsed source parameters are controlled via fiberoptic light links to the high voltage terminal.[2] In typical operation, this reliable, low-maintenance source produces a 100 μs beam pulse with a 10 μs rise time and 50 μs decay time.

The preaccelerator is a 4 MeV Dynamitron which has been modified extensively for maximum pulsed current operation at 1.5 MeV. A high gradient accelerating column is used to handle the large current density. A more complete description of the preaccelerator has been published.[3] The high gradient column initially had an outer shell consisting of ceramic rings which were epoxy-bonded to titanium rings with indium seals. It originally conditioned to 1.4 MV, but would not operate reliably above 1.2 MV because of excessive gradients between the protective rings along the inside surface of the outer shell.

The high gradient column is now in operation with a new outer shell. The gradients between the inner protective rings were reduced by almost a factor of two. The ceramics are longer, so there are only one-half as many joints. The joints are not bonded; C-rings with lead foil backed up by rubber O-rings make up the vacuum seals, with the entire column spring-clamped with 30,000 pounds of force. The ends of the ceramics are covered with copper foil to produce a uniform electric field across the face of the ceramic. So far, the column has been conditioned to 1.53 MV and 35 mA beam currents of Xe^+ have been accelerated to 1.5 MeV. This performance was achieved with one out of fifteen ceramics shorted - apparently it failed because of an internal defect. In general, the column now conditions very easily and deconditions little when turned off for several days. At a convenient time, the shell will be disassembled and a replacement ceramic inserted which should improve the long-term operation of the column at 1.5 MeV. Preaccelerator emittance measurements were performed using nondestructive profile systems [4] at the buncher waist followed by a drift space. The 90% envelope transverse normalized emittances were measured to be 0.027 cm-mrad at 1.5 MeV and 0.019 cm-mrad at 1.0 MeV. While the preliminary value at 1.5 MeV is larger than expected and may be reduced by further optimization, it is still more than adequate for HIF, and an order of magnitude brighter than other high current sources.

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Linac Cavities

The front end of the prestripper linac consists of a buncher, five independently-phased 12.5 MHz short, single-stub linac cavities, and three 12.5 MHz double-stub Wideroe linacs to reach 22.9 MeV. The layout through the first Wideroe linac is shown in Fig. 1. The linac is operational through IPC 3 where the energy is 2.2 MeV. The first Wideroe is partially constructed, but is now on hold because of budget constraints. A detailed design of the linac has been published.[5] The parameters of the prestripper linac sections are shown in Table I. The emittances and transmitted currents are results of a beam simulation using the PARMILA code. Note that essentially all of the emittance growth and beam loss have occurred by the end of the first Wideroe tank. For this reason a high priority had been placed on completing at least that much of the linac to study the beam properties.

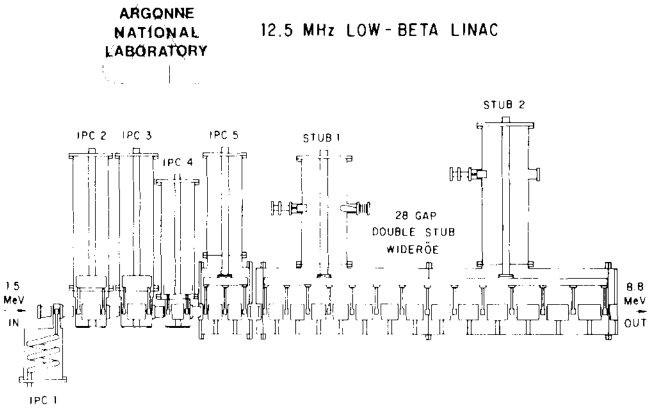

Fig. 1 Initial Cavities of HIF Linac. Five independently-phased cavities accelerate xenon to 3 MeV for injection into Wideroe.

Electroplating

The first three linac cavities were made of solid copper. We found that the fabrication costs of solid copper were essentially the same as using copper-clad steel because of the additional operations involved with the latter. However, it was clear that a copper electroplate on steel could reduce fabrication costs by at least one-third. To realize the maximum benefit would require the use of plating levelers and brighteners. These avoid the need of final polishing and greatly simplify plating around corners and into apertures. This technique has been very successfully developed at GSI in Darmstadt, West Germany for the large UNILAC cavities. A thorough search of vendors in this country revealed that only one was willing or capable of attempting the internal electroplating of large tanks using similar techniques. After studying the GSI process, the proposed vendor process, and an ANL in-house process, we have arrived at a modified electroplating procedure which encompasses the best features of each without exceeding the plant capability of the vendor.[6] As a test piece and prototype, the tank of stub #1 of the Wideroe has been electroplated successfully with 250 μm of copper. This tank is 0.91 m in diameter and 1.82 m in length with many apertures and flanges. The surface finish was leveled from 1.3 μm on the steel substrate to 0.25 μm after plating. The electroplate thickness was uniform (± 10%) and has excellent adhesion when subjected to heat and vacuum. The electrical conductivity is greater than 90% IACS.

Sparking Limit Test

A voltage sparking test was conducted using IPC 1 to determine the maximum surface electric field strength that could be reliably used at 12.5 MHz in linac design. Specifically, the test was conducted to determine by what factor the Kilpatrick voltage limit[7] could be exceeded without a great danger of sparking. In normal operation at 12.5 MHz, IPC 1 runs spark-free in a clean, high-vacuum environment up to 15 MV/m (1.6 times the Kilpatrick limit) with 30 mA of Xe^+ passing through it. In order to increase the gradient achievable in IPC 1 by nearly a factor of 2, a copper cap was added on one side of the drift tube to reduce its gap from 1.2 cm to 0.66 cm. Sparking tests with 1 ms pulse widths every 1.5 s were conducted for about a month. A spark rate of 1% was measured at 22 MV/m (2 times the Kilpatrick limit) and 28% at 25 MV/m (2.3 times the Kilpatrick limit). At these levels, there is about 2 joules of energy stored in the cavity. Protective circuits turned the rf drive power off on the occurrence of a spark, so that only the cavity-stored energy was dissipated in the spark. After high voltage conditioning, the cap had a sand-blasted appearance, with several tiny surface cracks and fissures visible. The results indicate that one should proceed with great caution before designing delicate structures or systems with large stored energy beyond twice the Kilpatrick limit at 12.5 MHz.

Status

IPC 2 AND 3 have internal 5π drift tubes; therefore, they are especially sensitive to the beam particle velocity. When we were limiting the operating voltage of the old accelerating column to 1.2 MV, this sensitivity led us to a two-stage procedure for studying the performance of the low-beta linac through IPC #3 using both xenon and krypton (with natural isotopic abundances).

The acceleration of 30 mA Kr^+ demonstrated the correct velocity profile and power and phase control through the linac. The preaccelerator energy was 0.98 MeV and the respective cavity exit energies were 1.09, 1.27, and 1.43 MeV. These energies have the velocities corresponding to the design for xenon from 1.5 MeV to 2.2 MeV.

At present, we are operating with 30 mA Xe^+ beams injected at the design energy of 1.5 MeV. The output energy of 2.2 MeV is achieved with nearly the expected power levels and phase angles. Accurate measurements of capture and beam characteristics will be performed using 80% enriched Xe^{129}.

TABLE I

PARAMETER	Independently-Phased Linac Cavities IPC #1	IPC #2	IPC #3	IPC #4	IPC #5	12.5 MHz Wideroe Linac Tank #1	Tank #2	Tank #3
Mode	$\pi/5\pi$	$\pi/5\pi$	$\pi/5\pi$	$\pi/5\pi$	$\pi/5\pi$	$\pi/3\pi$	$\pi/3\pi$	$\pi/3\pi$
No. of Gaps	2	4	4	4	6	28	22	34
Exit Energy (MeV)	1.66	1.95	2.21	2.54	3.00	8.84	15.65	22.90
$\sqrt{\epsilon_x \ \epsilon_v}$ (cm-mr)	0.066	0.067	0.069	0.070	0.071	0.087	0.090	0.088
ϵ_z (10^{-4} eV sec)	2.87	2.91	2.99	6.76	6.43	5.16	5.29	5.45
I (mA)	39.9	38.1	37.5	36.9	36.5	24.1	23.3	22.0
Shunt Imped. (MΩ/m)	3.6	6.1	6.4	10.5	15.6	32.7	24.5	51.6

Plans and Options

The program plan has been to install the former Princeton-Penn 3 GeV synchrotron magnet as a stacking ring as soon as the 8.8 MeV Xe^+ beam is available from the first Wideroe tank. Program options must now be considered because of reduced budgets and the introduction of new issues. At anticipated funding levels during this year, it will not be possible to continue any construction. Instead, we will concentrate on design studies dealing with the problem areas in the rf linac/storage ring scenario. One of the primary uncertainties in the storage ring concept for HIF is the potential problem of the longitudinal microwave instability caused by vacuum chamber impedance coupling to intense beams with little momentum variation. Studies are underway to devise experiments to measure the growth rates under controlled conditions.

There is a clear need for a definitive set of experiments to determine the maximum reliable gradients on conditioned electrodes over a wide frequency span. Experience at various laboratories indicates that the Kilpatrick limit is too conservative since it was based on non-conditioned surfaces in diffusion-pumped cavities. However, the same experience does not indicate a consistent pattern of maximum gradients as a function of frequency. We plan to carry out rf sparking experiments over the range of 10-100 MHz in the same apparatus using an existing very wideband power amplifier. It will incorporate a clean vacuum system and study conditioning under realistic conditions. The effects of different materials and surface preparations will be investigated.

An interesting HIF design using a radio-frequency quadrupole (RFQ) linac was recently completed.[8] If it can be economically constructed and made operationally reliable, the 12.5 MHz RFQ would accelerate 50 mA of Xe^+ from 0.30 to 10 MeV with only a factor of 2 emittance growth. We are presently working on the electrical and mechanical design of such a RFQ linac[9] which, if constructed, could make a direct comparison of its operation with our more standard approach.

We are considering beam experiments which could be done with our present system. These include wall evaporation rates due to particle irradiation, heavy ion ranges in plasma hot cells, and thin foil stability during irradiation. These all have interesting implications for HIF targets and reactors.

The development of improved diagnostics to accurately characterize these intense beams is needed. We plan to continue development in this area.

Finally, a detailed study of the optimal funneling of beams for filling rings is also needed. Some of the presently advanced scenarios would funnel the beams to such an extent that the cost of the required instantaneous rf power would be prohibitive for a power plant.

References

1. R. P. Vahrenkamp and R. L. Seliger, IEEE Trans. Nucl. Sci., NS-26, 3101 (1979).
2. J. M. Bogaty and R. Zolecki, IEEE Trans. Nucl. Sci., NS-28, 2350 (1981).
3. J. M. Watson, et al., IEEE Trans. Nucl. Sci., NS-26, 3098 (1979).
4. J. M. Bogaty, Ibid, 3349.
5. J. M. Watson, et al., IEEE Trans. Nucl. Sci. NS-28, 3449 (1981)
6. G. W. Klimczak, et al., 9th Sym. Eng. Prob. Fusion Res., (1981 to be published).
7. W. D. Kilpatrick, Rev. Sci. Inst., 28, 824 (1957).
8. R. H. Stokes, T. P. Wangler, and K. C. Crandall, IEEE Trans. Nucl. Sci., NS-28, 1999 (1981).
9. A. Moretti, et al., this conference.

Discussion

Once substantial pitting occurs, we find the part must be replaced. Outgassing rate measurements on copper-electroplated steel have been made at Los Alamos, and it appears to be the same as electroplated pure copper. Any procurement of this material should specify the required conductivity. We specified it be above 90% copper; it came out about 98%, for both dc and rf measurements. We have not studied the gap dependence of the sparking in this situation. We would like to do a consistent experiment using a wide-band power amplifier from the ZGS.