IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE STATUS OF THE ARGONNE HEAVY ION FUSION LOW-BETA LINAC*

J. M. Watson, J. M. Bogaty, A. Moretti, R. A. Sacks+, N. Q. Sesol, A. J. Wright
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL. 60439

Summary

The primary goal of the experimental program in heavy ion fusion (HIF) at Argonne National Laboratory (ANL) during the next few years is to demonstrate many of the requirements of a RF linac driver for inertial fusion power plants. So far, most of the construction effort has been applied to the front end. The ANL program has developed a high intensity xenon source, a 1.5 MV preaccelerator, and the initial cavities of the low-beta linac. The design, initial tests and status of the low-beta linac are described.

Introduction

The ANL program will demonstrate adequate solutions to as many as possible of the issues involved with the RF linac/storage ring approach to heavy ion fusion. The linac for the facility proposed to accomplish this objective is shown in Fig. 1. It is designed to accelerate more than 40 mA of Xe^{+8} to 220 MeV. The beam will then be debunched and multiturn injected into a stacking ring, reaching the space charge limit. Experiments on injection, extraction, beam losses due to residual gas and beam-beam collisions, and the various effects of such losses will be carried out.

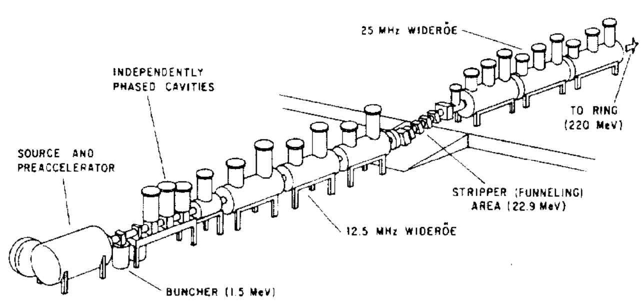

Fig. 1 The 220 MeV Xe^{+8} Linac for HIF Accelerator Development Facility

In addition to demonstrating the acceleration of the beam current needed for power plants, it will be necessary to limit the emittance growth. For a power plant driver, the normalized transverse emittance from the linac should be less than 0.15 cm-mrad. The preaccelerator beam has a normalized transverse emittance less than 0.02 cm-mrad and the numerical simulation discussed below indicates that most of the emittance growth due to nonlinearities in the accelerating and space charge fields occurs in the first few cavities. Further growth may also occur due to stripping to higher charge states, funneling of multiple linac beams, and linac frequency transitions. In the Accelerator Development Facility (ADF), these operations all occur at 22.9 MeV. A gas stripper will be used to produce an electrical current of more than 40 mA of Xe^{+8} which will then be matched into a 25 MHz Wideroe linac. The transition will include a vertical "dog-leg" to simulate funneling with a second 12.5 MHz linac beam into the 25 MHz linac. The study of emittance growth throughout the linac is an important part of the ADF program.

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^{+1} 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 preaccelerator has been operated extensively over the past year at 1.1 MeV. During initial operation the column conditioned to 1.4 MV. Above that, extensive arcing occurred across the protective rings along the vacuum side of the outer shell and many of the ceramics were chipped. The protective rings were modified to lower their surface gradients and an additional accelerating electrode was inserted to lower the voltage across the final gap to decrease the magnitude of spark down transients. Most operation since then has been at 1.1 MeV with 40 mA Xe^{+1} where it runs virtually spark-free. A new column outer shell is now being assembled and will be installed shortly. It is expected that even lower gradients and an improved ceramic-metal joint design in the new outer shell should allow operation at 1.5 MeV and 40 mA.

Preaccelerator emittance measurements were performed using nondestructive profile systems[4] at a waist followed by a drift space. The 90% envelope transverse normalized emittances were measured to be 0.019 cm-mrad at 1.0 MeV. This is expected to drop to 0.01 cm-mrad at 1.5 MeV, but is already adequate for HIF requirements and an order of magnitude brighter than other high current sources.

RF Linac Design

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 post-stripper linac consists of three 25 MHz triple-stub Wideroe linacs to reach 220 MeV. The parameters of the linac sections are shown in Table I. The output current could be increased to 80 mA by funneling an additional 12.5 MHz front end into the 25 MHz linac.

* Work supported by U. S. Department of Energy.
\+ Science Applications, Inc.

0018-9499/81/0600-3449$00.75©1981 IEEE

The layout of the current test stand plan is shown in Fig. 2. The present buncher (lumped inductor cavity) will become the first independently phased accelerating cavity.[5] A new harmonic buncher has been designed[6] to replace it. We anticipate that this improved buncher will increase the capture efficiency to 70%. The capacitively loaded cavity[5] now on the test stand will be modified to four gaps and become IPC #4. IPC #5 will be a 6-gap "drum" type linac cavity.[5] Initially, IPC #4 and #5 will have electrostatic quadrupoles, but are designed so that they can be easily refitted with magnetic quadrupoles.

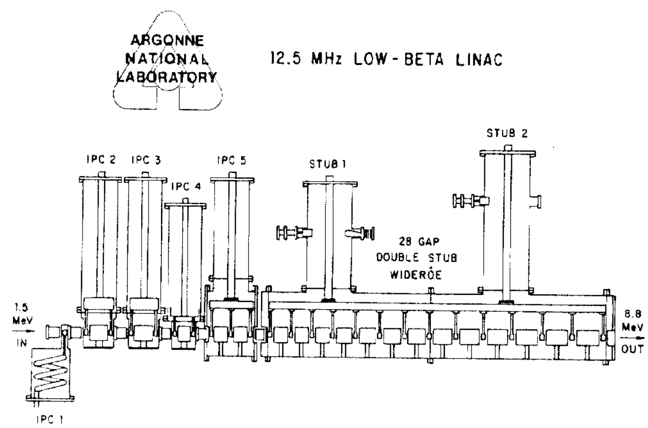

Fig. 2 Initial cavities of ADF linac. Five independently-phased cavities accelerate xenon to 3 MeV for injection into Wideroe.

The first 12.5 MHz Wideroe tank, containing 28 gaps, is currently under construction. The tank and all other tank parts, except for the quadrupole housing and "short" drift tubes, are made of mild steel and will be electroplated with 250 μm of high conductivity, bright copper. After studying the GSI process,[7] a 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. As a test piece and prototype, the tank of stub #1 of the Wideroe has been shipped to the vendor for plating. The plating procedure will be closely monitored; if satisfactory, it will be duplicated for the remainder of tank parts and all the remaining Wideroe tanks of the linac.

Beam Simulation

Numerical simulation of the beam behavior through the 12.5 MHz IPC's and Wideroe was performed with a locally modified version of the PARMILA code.[8] Initial beam parameters were assumed to be

x_0 = 2.086 cm	x_0' = 0.974 mr
y_0 = 1.171 cm	y_0' = 1.735 mr
$\Delta\phi$ = ± 35°	ΔT = 0.0262 MeV
I = 40 mA	T = 1.5 MeV

where all variations refer to phase ellipse semi-axes. The transverse dimensions are matched to a periodic transport line of the same cell geometry as the first cell in IPC #1; $\Delta\phi$ is the length of the stable region; ΔT corresponds to a 1% momentum spread.

The quadrupole gradients were tuned interactively to optimize beam current and brightness. The retained current and rms beam emittance as functions of accelerator cell number are shown in Fig. 3. Table I lists the resulting current and the transverse and longitudinal normalized emittances at the end of the section.

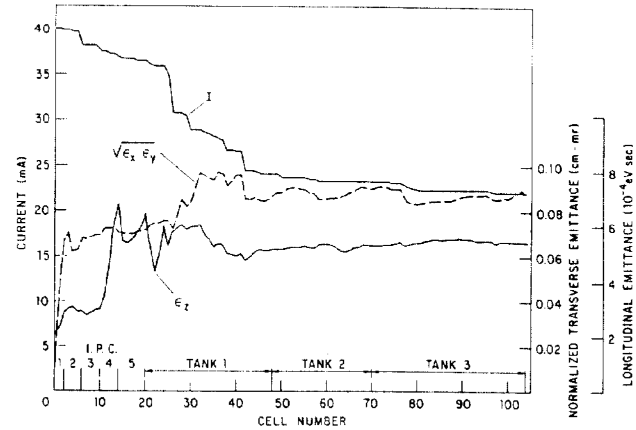

Fig. 3 Expected Xenon Current and Emittances Through 12.5 MHz ADF Front End

We have also invested substantial effort in parametric studies of alternative low-beta accelerator designs. Without detailing the actual studies performed, we list below the principal conclusions:

1) Contrary to widespread notions, for these high intensity beams there appears to be little advantage to using long, low energy gradient acceleration. For idealized linacs (constant energy gradient, transit time factors T = 1, S = 0) the 4-D beam brightness at 8.8 MeV versus energy gradient shows a very broad maximum at about 0.8 MeV/m.

2) There is, at least in principle, considerable room for technological improvement within the realm of drift tube RF linacs. In the ultimate run we have made, we find that a π/π FFODDO idealized linac with very high gradient electrostatic quadrupoles could accelerate 40 mA of Xe^{+1} from 1.38 to 8.8 MeV with a 99.7% capture efficiency and a transverse emittance growth of 6.7.

3) For realistic parameter values, achievement of high energy injection is crucial. When the injection energy was lowered to 1.38 MeV in an idealized linac system directly comparable to our engineering design ($\pi/5\pi$ FODO from 1.38 MeV to 3.07 MeV; $\pi/3\pi$, FOFODODO from 3.07 MeV to 8.90 MeV), the final current fell to 16.1 mA. This effect could, perhaps, be alleviated by introducing the acceleration slowly and smoothly in a manner similar to that envisioned for the shaper and gentle buncher sections of an RFQ.

Status

IPC #2 and #3 have internal 5 π drift tubes; therefore, they are especially sensitive to the beam particle velocity. Since we have been limiting the operating voltage of the old accelerating column to 1.2 MV, this sensitivity has 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^{+1} 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.

Full power operation was tested by injecting 30 mA of Xe^{+1} at 1.2 MeV and running the cavities at maximum power and at decreased accelerating phase angle. An output energy of 2.02 MeV was achieved in spite of the large phase slips encountered because of non-synchronous operation. This agreed with the projected energy gain and verified that the cavities were performing as expected.

Bunching efficiency measurements are complicated both by the off-design beam energy and by the isotopic mixture in natural xenon. At present, we measure a bunching factor of 4.5 at the position of IPC #1. The harmonic buncher should perform even better. Operation at 1.5 MeV and delivery of a bottle of 80% enriched Xe^{129} will allow more accurate measurements of capture and transmission.

The linac construction is presently paced by the available funding. IPC's #4 and #5 and the first Wideroe tank are awaiting additional funding for completion. The electroplating procedure development is continuing so that a more economical construction technique will be available for linacs by domestic vendors. The construction of a long Wideroe drift tube with internal magnet is also proceeding in an effort to resolve the construction details of an economical unit. Studies on the formation of CO_2 gas jets have started in preparation of designing the stripper.

Acknowledgements

We would like to express our appreciation to the HIF technical crew for the assembly and operation of the facility; to E. Colton, J. Dawson, S. Fenster, R. Lari, K. Menefee, J. Moenich and R. Stockley for design assistance; and to R. Burke, M. Foss, T. Khoe, R. Kustom and R. Martin for their guidance.

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TABLE I

	Independently Phased Linac Cavities					12.5 MHz Wideroe Linac			25.0 MHz Wideroe Linac		
PARAMETER	IPC #1	IPC #2	IPC #3	IPC #4	IPC #5	Tank #1	Tank #2	Tank #3	Tank #1	Tank #2	Tank #3
Mode	$\pi/5\pi$	$\pi/5\pi$	$\pi/5\pi$	$\pi/3\pi$	$\pi/3\pi$	$\pi/3\pi$	$\pi/3\pi$	π/π	$\pi/3\pi$	π/π	π/π
Focusing	FODO	FODO	FODO	FODO	FODO	FOFODODO	FODO	FOFOFODODODO	FODO	FOFODODO	FOFODODO
No. of Gaps	2	4	4	4	6	28	22	34	20	20	16
Length (m)	0.36	0.78	0.84	0.59	0.96	6.36	7.28	7.16	6.68	5.16	5.20
Peak Volt. 1st Gap (kV)	141	124	106	127	115	257	329	247	448	495	585
First Gap Width (cm)	1.20	1.50	1.50	1.50	1.55	3.78	6.47	3.83	5.26	4.93	9.93
First Cell Length (cm)	17.9	19.0	20.5	14.4	15.4	16.9	28.8	19.1	23.7	22.4	29.8
RF Power (KW)	23.2	24.0	18.8	24.5	24.8	302	427	312	775	896	1195
Shunt Imped. ($M\Omega/m$)	3.6	6.1	6.4	10.5	15.6	32.7	24.5	51.6	24.0	28.5	19.2
Exit Energy (MeV)	1.66	1.95	2.21	2.54	3.00	8.84	15.65	22.90	84.7	151.2	220.0
$\sqrt{\varepsilon_x \varepsilon_y}$ (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	-	-	-