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STATUS OF THE US HEAVY ION FUSION PROGRAM*

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Introduction

It is a pleasure to be able to come to Abingdon to help in this study of applications of the Spallatron Neutron Source (SNS) to problems of Heavy Ion Fusion (HIF). I feel that I am in a small way repaying those from Rutherford who have contributed so much to our US HIF workshops.

In order to review the US HIF program, it is necessary to discuss both the program elements and the political situation. I will start with the latter topic and then present the technical justification for the interest in HIF because it is assumed that not everyone in this audience has heard this story. This will be followed by a brief description of the Argonne Program to develop the rf linac storage ring system for which the SNS can contribute important data. Finally, I will describe the new direction being taken by the Berkeley group to develop the induction linac system.

Political Science

The politics of science (not the science of politics) seems to have achieved new levels of intensity in the US effort to develop inertial confinement fusion (ICF) as an energy source. Part of this is due to the view that ICF is a defense program firstly, and that defense funds should not be used for energy applications. This view is countered by

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the completely defendable strategy that the near term goal, to demonstrate that the concept works, is the same for both defense and energy. However, this strategy must be extended when talking of "advanced drivers," i.e., heavy ions or short wavelength gas lasers, that could become part of commercial electric power generation systems. One way of defending at least the HIF approach is to point out that both the energy and the defense applications need high yield, and according to the present status of target design, this requires driver energies of multimegajoules. Thus HIF could be promoted for the defense application on the basis of favorable cost scaling at high delivered energy. Those most interested in HIF are, however, interested in it for energy. Accordingly, the HIF program has been promoted mostly for energy and attempts have been made to get support from the congressional committees dealing with energy. HIF does, in fact, fit perfectly the Reagan Administration's description of the sort of high risk-high payoff research that should be government funded. Nevertheless, as this talk is given, there are reports that the HIF budget for FY 1982 may be zero. To our friends outside of the US, it should be pointed out that there are many "budgets" in any one year, written by various congressional committees and administration departments, and that the final budget, which is usually not known until at least the start of the fiscal year in October, is a result of many hearings, conferences and compromises. Therefore, do not be too quick to conclude that HIF is dead based only on one budget scenario. Even if the HIF budget should turn out to be zero in FY 1982, the technical justification is so strong that the idea will not die because of the loss of one year's funding. The experimental program would stop and the prospects for competing in a timely way with other fusion schemes would be severely damaged by such a cutoff. This damage could be partly alleviated by the progress you are able to make in Europe and Japan. If practical fusion energy is realized it will be used to benefit all nations, either directly or by reducing competition for scarce energy resources. Fusion is like a long journey: we are now just searching for the right path. The program suggested for the beam studies on the SNS will help in finding that right path, and it is welcomed by the rest of the ICF community.

Why Heavy Ions

The technical justification for interest in beams of heavy ions to ignite inertial fusion pellets has several key parts:

(1) The favorable range-energy relationships that permit high kinetic energy ions to be stopped in the target. The target coupling problem is expected to be completely classical.

(2) The established technology of accelerators resulting largely from 50 years of development of research accelerators for high energy and nuclear physics. Practical accelerators already have the efficiency (10-30%) and repetition rate (10-30 Hz) needed for commercial power plants.

(3) The favorable scaling of cost vs energy (joules) as target requirements for reasonable gain have gone to the multimegajoules level.

(4) Computation results indicating that the final transport problem, i.e., hitting a target in a practical reactor environment, is solvable provided the beams of heavy ions are divided into enough beamlets of adequate beam quality.

Although modern accelerators and storage rings can easily store beams in the megajoule range, the particular problem of the high peak power level requires extensions of existing experience. The new theoretical and experimental work needed for HIF is in the area of handling the very high peak intensity, space charge limited beams.

A 10 GeV ion of mass 200 has a range of about 0.2 g/cm^2. This is about the same range that a 10 MeV proton would have, so if the proton beam could be focused as well as the heavy ion beam, one would require a proton beam of 1000 times the peak current of the heavy ion beam. In practice, the high current proton beams will probably be significantly larger in cross section, requiring specially designed targets and transport systems as well as somewhat higher beam current and delivered energy. It is easier to make a direct comparison between heavy ions and short wavelength ($\lesssim 0.25$ μm) lasers as shown in Figs. 1 and 2. In addition to the "realistic" zone for short wavelength lasers (between the dashed lines) the figures have curves for the parameter $r^{3/2}R$, where r is the target spot radius (cm) and R is range (g/cm^2). A target spot of about 0.15 cm radius would be needed with 10 GeV ions to achieve $r^{3/2}R \approx 0.01$. At this level the heavy ion target performs essentially as well as a comparable laser target. The two sets of curves were prepared by Bangerter[1] and illustrate also the difference between single and double shell targets. Although higher gains are theoretically possible with double shell targets, these more complex systems also exhibit a steep threshold at 3-4 MJ below which they fail.

To achieve economically feasible commercial electric power, the amount of circulating energy in the entire plant must be kept below about 33% of the total energy output. Since the thermal-to-electric conversion efficiency is also about 33%, this results in a requirement that the target gain times the efficiency of the driver (electrical mains to pellet) must be $\eta G \geq 10$. From the figures, one sees that $\eta G = 10$ could be achieved by heavy ion beams of 3-4 MJ for either single or double shell targets if a nominal 25% is used for the accelerator conversion efficiency. Such targets would yield about 120-160 MJ per shot. For laser systems, on the other hand, because of their much lower conversion efficiency ($\leq 5\%$) only double shell targets can be used and even then the beam energy must be 8-10 MJ yielding 1600-2000 MJ per shot; 2000 MJ is equivalent to the energy in 1/2 ton of high explosive! Furthermore, such systems cannot even be tested at less than 3-4 MJ because of the threshold at that energy.

The Argonne Program

The primary goal of the experimental program in HIF at Argonne National Laboratory during the next few years is to demonstrate many of the requirements of a rf linac driver for inertial fusion power plants. It is planned to construct an Accelerator Demonstration Facility (ADF) in the building vacated by the ZGS accelerator as shown in Fig. 3. This discussion of the status of this work is taken from the recent paper by Watson *et al.*[2]

So far, most of the construction effort has been applied to the front end. The Argonne program has developed a high intensity xenon source, a 1.5 MV preaccelerator, and the initial cavities of the low-beta linac. The linac for the facility proposed to accomplish this objective is shown in Fig. 4. 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.

The studies are planned with Xe^{+8} in order to achieve reasonable ion energies with a short, relatively low voltage linac. A real HIF driver probably would have ions of charge state +1 or, at most, up to +4.

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 numerical simulation indicates that most of the emittance growth due to non-linearities 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 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.

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.

Preaccelerator emittance measurements were performed using a nondestructive profile monitor 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.

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 output current could be increased to 80 mA by funneling an additional 12.5 MHz front end into the 25 MHz linac.

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. 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 magnets 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.

Berkeley Program

The program for developing an induction linac driver at the Lawrence Berkeley Laboratory has been redirected to incorporate the concept of multiple electrostatic focused beamlets as proposed by Al Maschke (BNL) for the rf low-beta accelerator. Individual beamlets using electrostatic quadrupoles are formed with their spatial pulse lengths (a few meters), equal to, or only slightly longer than, the spatial pulse length desired at the target. Pulse compression is achieved by simply restraining the pulse length from growing as the beam is accelerated. Thus, for example, if the beam kinetic energy is increased by a factor of 100, the velocity and hence, the current, are increased by a factor of ten. The transverse focusing system, consisting of small-aperture electrostatic quadrupoles with relatively modest voltages (a few kilovolts), is unchanged by the acceleration process with only one significant exception; the periodic length is increased proportional to beam velocity. Transverse dimensions, beam profile, focusing fields, are all unchanged so long as the linear density is unchanged.

The acceleration process occurs in short gaps, defined by metal plates with an individual hole for each beamlet as shown in Fig. 5. The effects of adjacent beamlets on each other are shielded except in the acceleration gap where they are canceled, to first order, by the presence of beamlets on all sides. At the outer edge of the array, some field shaping can be used to simulate an infinite array of beamlets. Moderately large aperture induction modules are envisioned, up to about one meter diameter, spaced as close as their requirements for linear space allow. Electrostatic quadrupole arrays and pumping systems are interspersed between accelerating modules.

The advantage of the multiple beamlet electrostatic quadrupole transport system is that the current that can be transported is a better match for the impedance of the induction linac. This is especially true at low energies, where the velocity of the ions is so low that long, low-current pulses would require uneconomically long pulse lengths. Although it is possible to ultimately combine beamlets into larger bunches, there is no obvious reason why the individual beamlets could not be transported from ion source to target pellet.

An artist's conception of a section of multiple beamlet quadrupole structure is shown in Fig. 6a. In Fig. 6b, the cross section of the ends of the rods are drawn showing the flattened sides facing the beamlets. A computer plot of the equipotential lines in a single quadrant are shown in Fig. 6c. This configuration results in focusing fields that are linear to within ±1% over more than 95% of the aperture.

If the current transported increases only with velocity, i.e., there is no bunching other than the pulse shaping needed to maintain constant bunch length, then the transverse focusing strength needed is independent of velocity. The length of a quadrupole period, however, must increase proportional to velocity. Thus, a number of quadrupole structures, such as that in Fig. 5, are at the same polarity until a length corresponding to half a period has been achieved, at which point a similar number of quadrupoles is set to the opposite polarity. In this way the electrostatic quadrupole can compensate for the relatively weaker focusing strength, compared to magnetic focusing, at higher velocities.

Constant bunch length requires that the average velocity of the head and tail of the bunch be the same: thus, the particles at the tail of the bunch have a higher energy $\delta E = \ell \, dV/dZ$ (where ℓ is the length of the bunch and dV/dZ is the average accelerating gradient). This energy increment needs to be imposed only once, at injection, and must be adjusted only if the accelerating gradient changes.

The space charge depression in the middle of a long beam acts to try to push the beam apart at the ends. The beams proposed here are a few meters long. It is planned to put small "ears" on the accelerating waveforms to confine the beams longitudinally. The ear at the leading edge is just a slightly delayed pulse, not accelerating the front of the pulse, and is essentially free. The ear at the trailing edge must "push" by an average field as great as the space charge depression divided by the (assumed) linear ramp length of the tail of the beam. The space charge depression is given by 30 I/B, which is a constant in this concept amounting to a few hundred volts. If the tails of the bunches are a few centimeters long, the ears are a few kilovolts per meter.

It is on this point of longitudinal confinement that another advantage of the multiple beamlets becomes evident; if all the charge is in one large "sausage" as in earlier concepts, the longitudinal ears are much larger. The problem then becomes a three-dimensional one of confining a short, fat sausage of charge rather than the long, thin "conventional" bunch suggested here.

The final focus system and the transport of the beam to the target appears to be surprisingly easy with the many small beamlets. Since the individual beamlets can be separately aimed at the pellet, the problems of large aperture chromatic and third order aberrations are all essentially eliminated. The space charge limited current that can be directed to a target (typically 2.5 mm radius at a distance of 10 m from the final lenses) is about 40 A from a beamlet with initial radius of about 1.0 cm. This assumes 10 GeV heavy ions with atomic mass above 200. This is comfortably above the needed current per beamlet and, furthermore, a large cluster of beamlets, an array of perhaps 1 meter diameter, could also be focused to such a spot with nearly two times the total current that is required.

The next step, which is in a preliminary design phase, is to build a small version of the full-sized driver. It could be perhaps a 100 MeV model carrying about 10% of the charge needed for a full-sized machine but including all the essential components. It is interesting to note that ions of any charge or mass can be accelerated with this system; thus for middle weight ions, such as sodium, higher beam power can be achieved with a low-energy accelerator. The ions would still have adequately short range and, as has been shown by Jim Mark of LLNL, interesting temperatures in excess of 100 eV can achieved by focusing the beam on a sufficiently small spot. Electron neutralization of the final beam can be used to avoid space charge spreading.

The present Berkeley experimental program involves extending the results reported[3] for the cesium drift tube linac to multiple beam operation and, simultaneously developing a "single beam" electrostatic quadrupole beam line to test the transport limit of such as system. This experiment, which will be done with cesium, is otherwise similar to the experiment proposed at Rutherford by John Lawson with a scaled down structure transporting an electron beam.

References

1. R. Bangerter, private communication. The target gain curves will appear in the 1980 Laser Program Annual Report from Lawrence Livermore National Laboratory.

2. J. M. Watson et al., Proceedings of the 1981 Particle Accelerator Conference, IEEE Transactions on Nuclear Science, to be published.

3. W. Chupp et al., Proceedings of the 1981 Particle Accelerator Conference, IEEE Transactions on Nuclear Science, to be published.

Figure Captions

Fig. 1 . Target gain as a function of input energy for single-shell targets. Curves for heavy ions are shown for the parameter $r^{3/2}R$, where r is target spot radius (cm) and R is range (g/cm^2). The heavy ion simulations are valid for $0.1E^{1/3} < r < 0.2E^{1/3}$, where E is in megajoules.

Fig. 2 . Target gain as a function of input energy for double-shell targets. The areas between the dashed lines represent the expected range of operation for short wavelength lasers. For heavy ions (mass > 200) at 10 GeV in a spot of radius 0.15 cm, $r^{3/2}R \approx 0.01$.

Fig. 3 . The beam development facility at Argonne. The injector and preaccelerator are operating and construction is proceeding on components up to and including the first 12.4 MHz Wideroe tank.

Fig. 4 . The 220 MeV Xe^{+8} linac for the Argonne beam development facility. Components up through the first two independently phase cavities, IPC #1 and #2, are installed.

Fig. 5 . Sectional view of an induction linac with a multiple electrostatic quadrupole focusing systems. Acceleration gaps are fitted with plates perforated with holes for individual beamlets.

Fig. 6a. Multiple quadrupole array showing one mounting scheme for the rods.

6b. Cross section view of part of the multiple beam array.

6c. One quadrant showing electrostatic equipotential lines. The flatsided rods have nearly linear fields over most of the aperture.

TARGET GAIN AS A FUNCTION OF
INPUT ENERGY FOR SINGLE-SHELL TARGETS

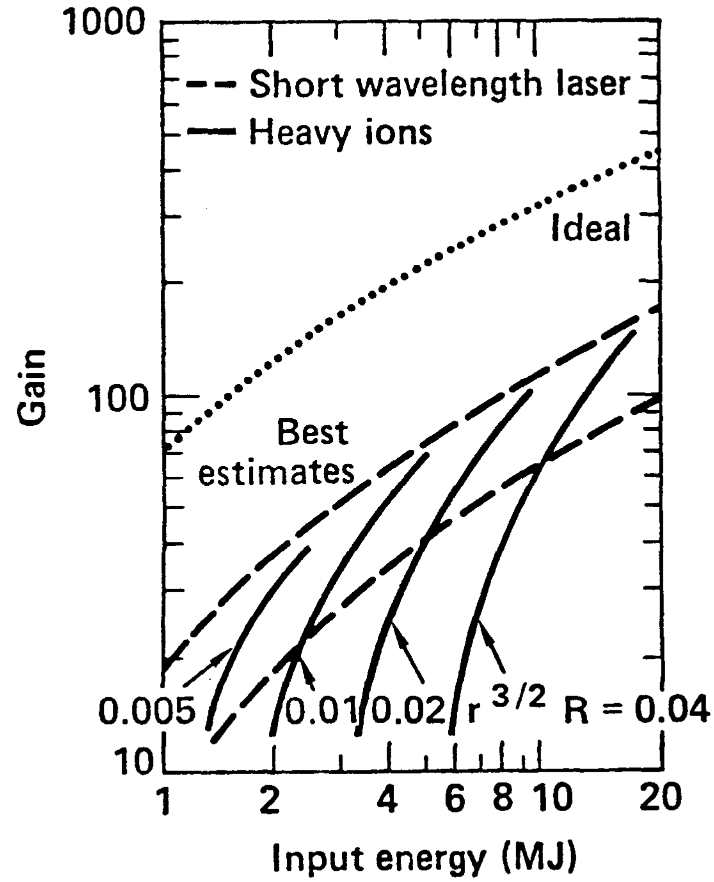

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Fig. 1

TARGET GAIN AS A FUNCTION OF
INPUT ENERGY FOR DOUBLE-SHELL TARGETS

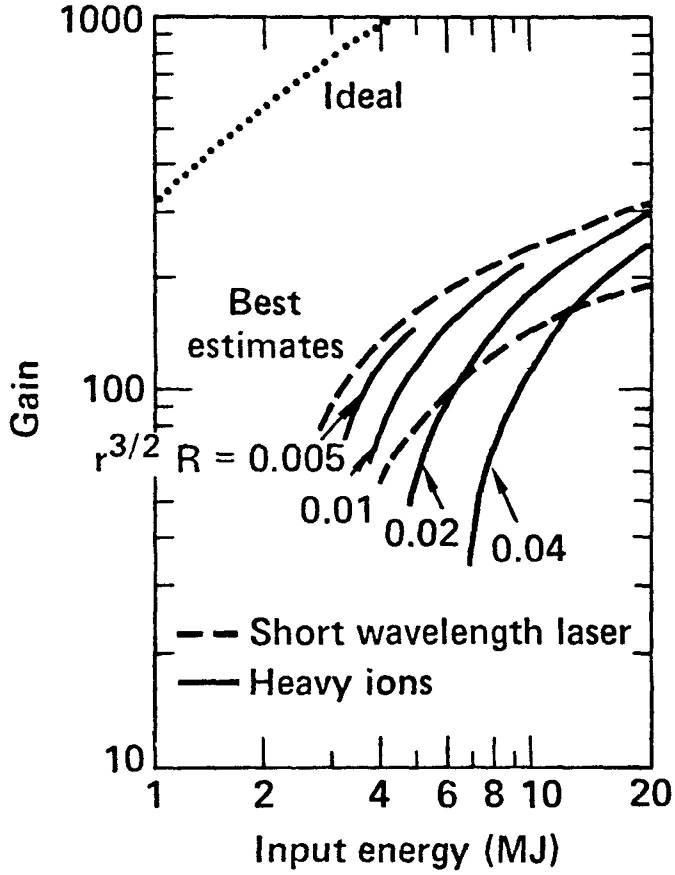

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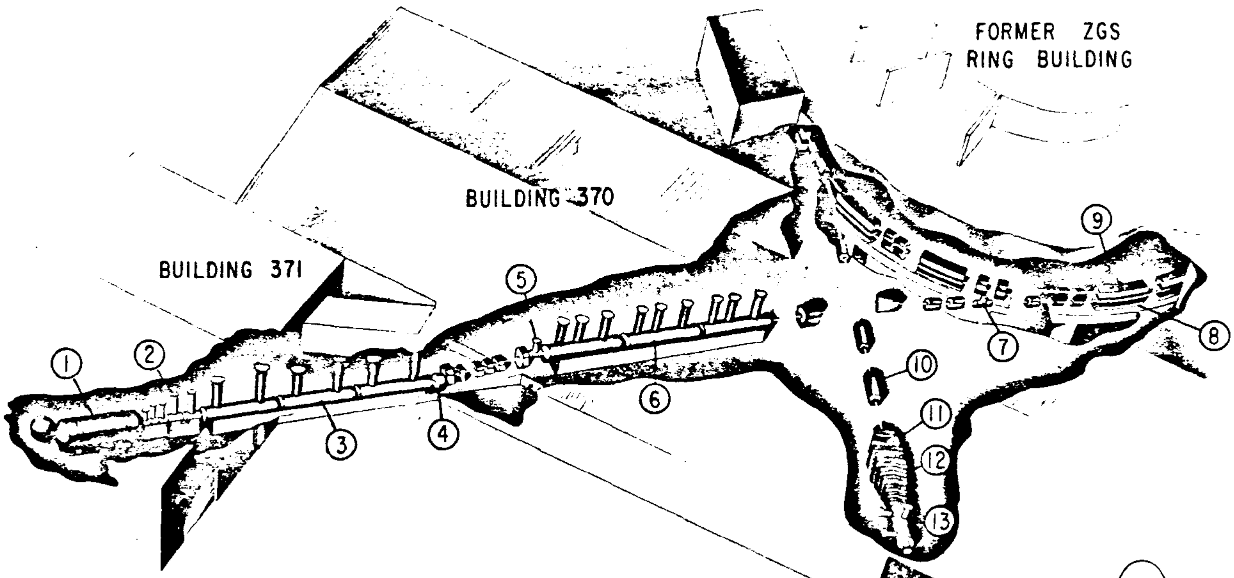
Fig. 2

HEAVY ION FUSION

BEAM DEVELOPMENT FACILITY

RF ACCELERATION SYSTEMS



ARGONNE NATIONAL LABORATORY

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LEGEND

1. SOURCE AND PREACCELERATOR
2. Lo β LINAC
3. 12.5 MHz WIDEROE
4. STRIPPER
5. RF BEAM COMBINER
6. 25 MHz WIDEROE
7. DEBUNCHER
8. INJECTION RING
9. STORAGE RING
10. TRANSPORT
11. SPLITTING
12. FOCUS
13. ENERGY DEPOSITION

Fig. 3

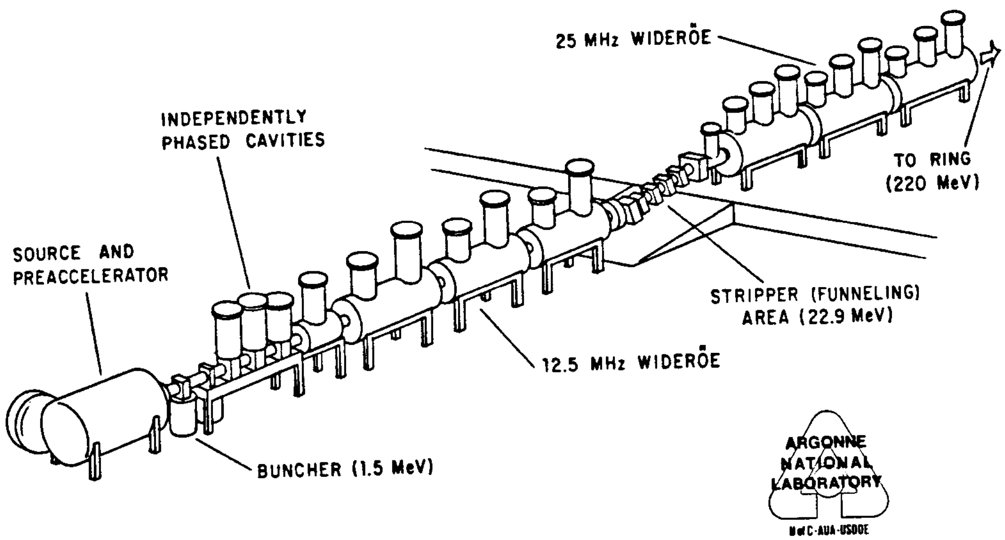
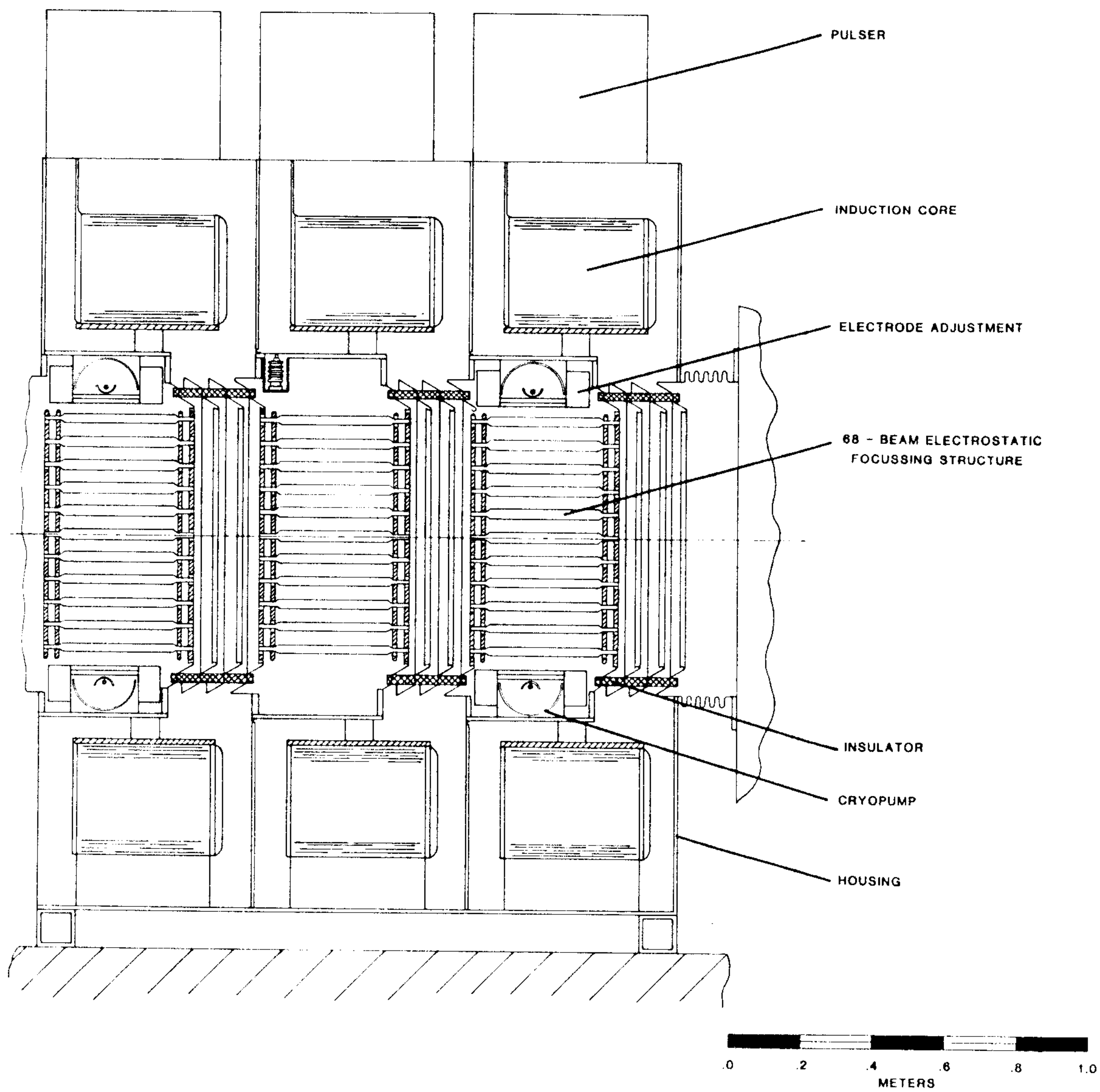

25 MHz WIDERÖE
INDEPENDENTLY
PHASED CAVITIES
TO RING
(220 MeV)
SOURCE AND
PREACCELERATOR
STRIPPER (FUNNELING)
AREA (22.9 MeV)
12.5 MHz WIDERÖE
BUNCHER (1.5 MeV)
ARGONNE
NATIONAL
LABORATORY

Fig. 4



MULTIPLE BEAM INDUCTION LINAC - SIDE SECTIONAL VIEW

XBL 813-8779

Fig. 5

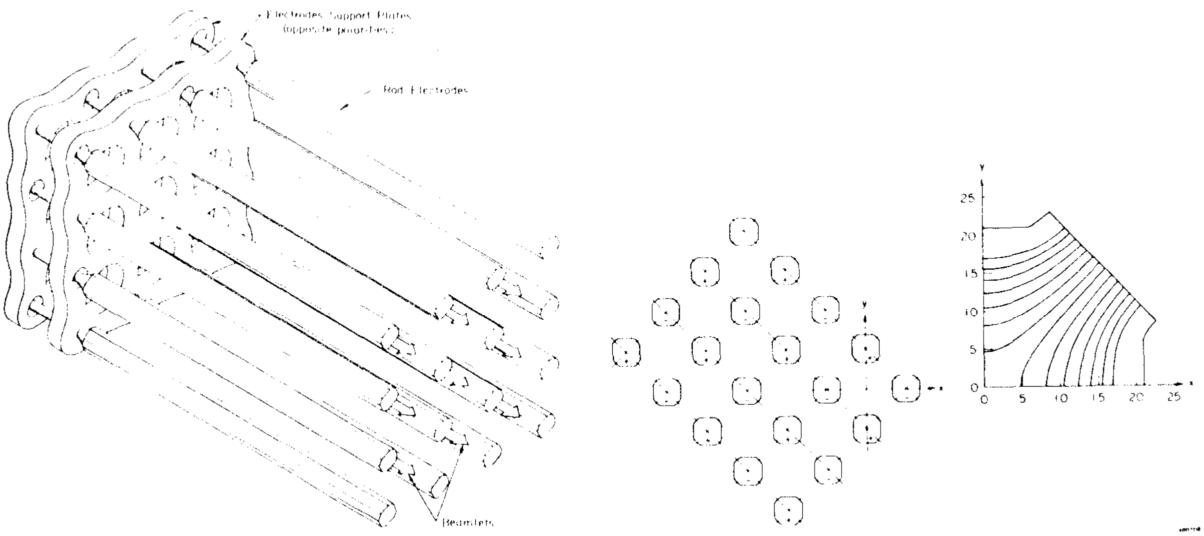

Electrodes Support Plates
Rod Electrodes
Beamlets
y
x
25
20
15
10
5
0
0
5
10
15
20
25

Fig. 6