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HEAVY ION ACCELERATORS FOR INERTIAL FUSION

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Abstract

Heavy ion beams make a good driver for inertial fusion. Two types of accelerator are promising for delivering the requisit high current beams - the rf linac/storage ring system pursued at the Argonne National Laboratory and the induction linac scheme developed at the Lawrence Berkeley Laboratory. The progress at these laboratories is, however, regrettably slow due to lack of funding. The general requirements on the driver for heavy ion fusion are reviewed and the status of various R&D efforts is discussed.

Introduction

It has been recognized for some years[1] that heavy ion beams make a good, perhaps the best, driver for inertial fusion when compared to photon (laser), electron and light ion beams. Briefly the advantages are:

1. For the fusion target

Compared to photons the physics for energy deposition by charged particles in the target material is much better known. The range of a charged particle in the target is shorter for higher particle mass. Thus, a heavy ion can carry more energy without penetrating too deeply into the tiny fusion target and a lower current of heavy ions is needed to supply the high power required.

2. Driver technology

The technology of accelerators and transports of charged particle beams is well established. Accelerators are operated steadily at high repetition rates with high reliability, a mode appropriate for a power plant. The conversion efficiency from electric energy to beam energy is high, possibly up to 25%. Except for the beam current all other parameter values necessary for heavy ion fusion (HIF) are well within existing experiences.

Despite these advantages HIF is nevertheless a late comer to a many pronged program toward fusion energy (see Fig. 1) with several approaches close to "breakeven". It is understandable that the launching of an R and D program for HIF has not been smooth and expeditious. In this paper we will describe the heavy ion accelerators that are being developed as drivers for HIF and the status of various efforts devoted to this task.

Target Requirements

Requirements on the heavy ion beams are imposed by both physics and economics; the former on the energy, power, emittance and momentum spread of the beams; and the latter on the target gain and the efficiency of energy conversion from a.c. main to beam.

Fig. 2 gives the energy circuit of an Inertial Fusion Power Plant and shows that $f\varepsilon\eta G = 1$. The thermal/electric conversion efficiency ε is no more than 30% and economics dictates that the factor f of the energy released by the pellet which is recirculated back to run the plant be no more than $\frac{1}{3}$. Hence we get the economics requirement

$$\eta G \geqslant 10.$$

If the driver efficiency η is no more than 20%, the target gain G must be $\geqslant 50$.

The physics requirements on the heavy ion beams are dependent on the design of the target and are, therefore, more difficult to derive. A great deal of effort has gone into such studies and improvements are continually being made on the target design. The published result[2] is given in Fig. 3 where the target gain G is plotted as a function of the beam energy W (in MJ) for different values of $r^{3/2}R$ with r = beam spot radius (in cm) and R = range of ion in target (in g/cm^2). Together with W the parameter $r^{3/2}R$ is roughly related to the density of energy deposition in the target. We see that even conservatively a gain of G>100 is within reach. More recent effort gave a further slight improvement. For design of the driver we need in addition, the range/energy curves for different ion species given in Fig. 4. In this paper we will take as example the following set of parameters.

Beam energy = W = 3 MJ
Pulse duration* = τ = 20 nsec
Beam power* = P = $\frac{W}{\tau}$ = 150 TW
Ion charge state = q = 1 } (U^{+1})†
Ion mass number = A = 238 }
Ion kinetic energy = T = 10 GeV
Beam current on target = 15 kA
Range in target = R = 0.1 g/cm^2
Beam spot radius on target = r = 0.25 cm
$r^{3/2}R$ = 0.0125 g/$\sqrt{\text{cm}}$
Target gain = G = 60 (conservative)
Minimum driver efficiency = η = 17%
Electric energy generated = $(1-f)\varepsilon GW$ = 36 MJe
Plant power output = 360 MWe (at rep. rate 10 sec^{-1})

*With multiple beam bunches on target any required pulse shape can be approximated by staggering bunches of different lengths. For simplicity here we assume a square pulse.

†This choice is no more than an example. Any ion specie with A >200 and q = 1 or 2 is perfectly acceptable.

Final Transport

We shall not discuss the drifting of the beam inside the reactor. It suffices to state that several transport pressure windows appear available for efficient transport and that neutralization actually makes the pressure windows even more adaptable to accelerator and target requirements. The most tractable, however, is the hard vacuum (<10^{-4} Torr) in which beam stripping, ionization, neutralization, and plasma effects and instabilities are all negligible. The focusing requirement gives directly the allowable emittance. With a beam spot radius of r = 0.25 cm and assuming a maximum allowable semi-convergent cone angle of 24 mrad which corresponds to a beam radius of 12 cm at the reactor wall some 5 m away, we get an (unnormalized) emittance

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limitation of

$$\varepsilon < \pi(60 \times 10^{-6})\text{m-rad}.$$

With a FODO magnetic quadrupole channel 50% filled with superconducting quadrupoles operating at a pole field of 4T and with phase advance per cell depressed from 60^o to 24^o, one can transport[3] a maximum current of 3.25 kA in an aperture radius of 3.2 cm. Thus the required 15 kA must be transported in ≥5 beams. We have taken a conservative phase advance depression. Recent work by I. Hofmann indicates that a depression from 60^o down to 12^o or even to 6^o is useable.

A sizeable amount of beam compression, hence current magnification, can be achieved in the final transport. Considerations of chromatic aberration demand that the momentum spread $\frac{\Delta p}{p}$ or equivalently the velocity spread $\frac{\Delta v}{v}$ be limited to

$$\frac{\Delta p}{p} \cong \frac{\Delta v}{v} < \pm 1\% .$$

With a velocity tilt along the length of the beam bunch such that the tail is 2% higher peak-to-peak than the head, the bunch can be compressed from, say, 60 nsec down to 20 nsec in a transport which is 3000 nsec or 260 m long. Thus, the accelerator is required to produce N_b beams each with

$$\text{Current} = \frac{5000}{N_b}\ \text{A} \qquad (N_b \geqslant 5)$$

Length = 60 nsec = 5.2 m

Emittance $< \pi(60 \times 10^{-6})$ m-rad

Momentum spread $< \pm \frac{1}{3}\%$

Momentum tilt: linear with bunch tail 2% peak-to-peak higher than head.

Only linacs are considered suitable for this application. Acceleration in a synchrotron is too slow when compared to the charge exchange lifetime of the ions in the beam which may be as short as a few tens of msec. Two types of linac are being pursued - the rf linac and the induction linac.

RF Linac and Storage Ring

We have much more experience with rf linacs for both light and heavy ions, but the beam current obtainable is low, generally only a few hundred mA. Thus, to supply the requisit hundreds of amperes a storage ring system is needed for current multiplication. The basic scheme is as follows:

1. Injection from a "funnel" linac system. One begins with 2^n beams each of current I_s supplied by 2^n ion sources and accelerated by 2^n Wideröe linacs operating at a low rf frequency appropriate to the very low velocity. They are then "funneled" by n stages of binary combinations into linacs with frequencies doubled at each stage. The total output current of this injector is $2^n I_s$ which is then also the output current of the main Alvarez linac at 10 GeV.

2. Transverse stacking a total of S turns (multiturn injection of $\sqrt{S}$ turns into each of the two transverse planes) into each of N_S storage rings. Stacking in both planes may require two stages of storage rings - one horizontal, one vertical.

3. Bunching and compression in the storage rings to give N_C bunches in each ring compressed in length by a factor C.

The total procedure gives $N_b = N_S N_C$ beams each having a current of $I = 2^n I_s SC$. Typical numbers could be I_s = 20 mA, n = 4, S = 10 x 10, C = 10, N_S = 2, N_C = 9. This gives 18 beams at 320 A each. Together with the factor 3 compression in the final transport this amounts to a total of 17.8 kA allowing some beam loss over and above the 15 kA required. At each stage of the operation the emittances of the beam must be smaller than the phase areas available or allowed by target requirements.

At injection in the storage rings the space charge detuning is small. But as the beam is compressed the increasing peak current will depress the betatron oscillation tune across all sorts of resonances including the integer and will exceed the threshold of longitudinal microwave instability. But since the compression is rather fast, taking place within only a few msec, neither of the space charge effects mentioned are expected to cause any emittance growth.

Although we have had a grest deal of experience with rf linacs and storage rings, the high beam currents involved are beyond existing experience. However, existing experience does show that the physics for current scaling in these machines is well understood and totally trustworthy. Nevertheless, the many beam manipulations required for current multiplication, such as funnel-combination, multiturn injection and longitudinal compression are rather complex and exacting. One can expect that a lot of operating experience must be gained before the operation of such a system can be made reliable and routine.

Induction Linac

Induction linacs are appropriate for high current beams, but have so far been used only to accelerate electrons. Many kA of tens of MeV electron beams have been attained. For heavy ions the main difference is the much stronger transverse focusing required because of the extremely non-relativistic low velocity. Thus for heavy ions the induction linac would basically be a long straight beam transport. The beam is accelerated along the way by pulsed transformer cores (induction modules) with the beam forming the single turn secondary. It has the advantage of simplicity in principle and the capability of producing the necessary high current beam directly without storage rings. Starting as a fairly high current but very long beam pulse, the beam bunch can be compressed by a linear tilt in energy along its length while it is being accelerated and ends up as the high current and very short pulse required. At the 10 GeV end the linac, assumed to be the same $60^o \to 24^o$ FODO channel as the final transport, can handle a 5 kA beam only with a larger emittance of about $\pi(120 \times 10^{-6})$ m-rad. The beam must then be split into, say, 4 x 4 = 16 beamlets each with emittance $\pi(30 \times 10^{-6})$m-rad and initial current 5/16 kA, and transported by 16 separate final transports.

The difficulty with the induction linac approach is largely technical. Since no heavy ion induction linac has been built, much of the technology, especially that for the very low velocity injector which has never been addressed for electrons must be invented or developed. The concept of LBL for an injector is to start with a large area contact ionization source producing a 4 A, 75 μsec pulse which is accelerated to 10-15 MeV by a series of long pulsed drift tubes. This beam which may have been compressed, say, by a factor 3 to 25 μsec and 12 A is then injected into the linac. Because the current and the length of the beam pulse varies from 12 A and 25 μsec at the beginning to 5000 A and 60 nsec at the end, the induction cavities must vary in design and the core material will change from laminated steel to ferrite to ferritic glass along the length of the linac. After exit from the linac, the 10 GeV beam is given a ±1% momentum tilt by a series of buncher cavities, then split into $4 \times 4 = 16$ beamlets by septa.

Although straightforward in concept a great deal of technological innovation is required for both the injector and the linac proper. Provided that the technological problems are satisfactorily resolved and the components operate reliably, the operation of the induction linac system could be relatively simple. The only delicate beam manipulation involved is the 16-way splitting at the exit of the linac. The longitudinal resistive instability of the single high current beam bunch also needs further study.

Recent Innovations

As mentioned earlier the most difficult component of a high current heavy ion linac is the injector. To supply adequate focusing at these extremely low velocities it is best to use electrostatic quadrupoles. Recently two suggestions of new applications were made which are worth noting.

1. Self-focusing linac structures

In a normal linac the fields in accelerating gaps are cylindrically symmetric and hence radially defocusing. This must be overcome by adding electric or magnetic quadrupoles. It has been recognized in the USSR for sometime that by abandoning cylindrical symmetry one can obtain a radial electric quadrupole component from the accelerating field to serve as a self-focusing structure. Several different configurations were proposed.[4] The most successful so far seems to be the Radio-Frequency Quadrupole (RFQ) structure proposed by Kapchinskii and Teplyakov and recently tested with good success at LASL[5]. Conceivably such an RFQ structure can be used to replace both the electrostatic accelerating column and the "funnel" system of Wideröe linacs as the injector in the rf linac scheme. For induction linacs one can install "finger" electrodes in the gaps of induction cavities to form quadrupole fields similar to that suggested by Vladimirskii for drift tube linacs. The whole area of self-focusing structures should be more thoroughly explored for possibilities of further simplifying the linacs and the injectors.

2. Multiple-beam electrostatic quadrupole arrays

For given phase advance depression the maximum current that can be transported in a quadrupole channel with fixed pole field is proportional to the aperture radius and not the aperture area[3]. This suggests that by dividing a big beam covering a large aperture area into many smaller beamlets individually focused and covering the same aperture area one gains in total maximum current transported as the number of beamlets. This is difficult to manage for magnetic focusing because it is hard to maintain the magnetic field as the aperture gets smaller. But it is easy to keep the electrostatic pole field fixed or even increasing as the inverse of the aperture radius, i.e. fixed pole voltage. This is precisely the arrangement desired for low velocity ions. The scheme of using a bundle of beamlets individually focused by electrostatic quadrupoles was first proposed by A. Maschke[6] for use in rf linacs and was named MEQALAC, the acronym of Multiple-beam Electrostatic Quadrupole Array Linear ACcelerator. Recently W. Herrmannsfeldt suggested applying the scheme also to induction linacs.

Current Efforts in the U.S.

The work in the U.S. is suffering from lack of funding. The total budget for this fiscal year is only \$5 million to be divided among some six laboratories. The budget for FY82 is not yet determined, but there are strong indications that it will be lower than this year, possibly no more than \$3 million.

The Los Alamos Scientific Laboratory has been assigned as lead laboratory for HIF with responsibility for planning, coordinating and managing the nationwide program. The work now in progress at various laboratories are briefly described below.

1. Argonne National Laboratory

The rf linac/storage ring approach is being championed at Argonne. As a test for the injector concept and design, and to eventually provide a facility to study the various beam manipulations necessary in the rf linac/storage ring scheme ANL has constructed and operated a dynamitron charged accelerating column followed by three 12.5 MHz independently phased cavities[7]. Singly charged xenon ions are produced in a Penning discharge source and have been accelerated to yield a 2 MeV, 40 mA beam in this combination. Fig. 5 shows a picture of this equipment. Two more independently phased cavities will be added to bring the beam energy to 3 MeV, at that point the beam will enter three 12.5 MHz double-stub Wideröe linacs to reach 22.9 MeV. At this energy the ions will be stripped to Xe^{+8} and further accelerated by three 25 MHz tripple-stub Wideröe linacs to reach 220 MeV. Radial focusing is supplied by magnetic quadrupoles. The whole setup is shown in the drawing of Fig. 6. Numerical computations give a normalized transverse emittance of 0.9×10^{-6} m-rad, a longitudinal emittance of 5.2×10^{-6} eVsec and a current of 24 mA for the 8.8 MeV beam at the end of the first 12.5 MHz Wideröe linac, and not much change from this point on. Cavities number 4 and 5, and the first Wideröe linac are in various stages of construction.

The operation of funneling two beams into one linac operating at twice the frequency will be tried and studied in detail at the entrance to the 25 MHz Wideröe linac. The 220 MeV Xe^{+8} beam will be used to study the operation of beam stacking in both transverse planes, beam longitudinal compression and various beam instabilities using as a storage ring one constructed out of the old Princeton Proton Accelerator magnets. If funding is further postponed these studies could be carried out with the 8.8 MeV beam after the first section of 12.5 MHz Wideröe linac.

2. Lawrence Berkeley Laboratory

The induction linac scheme was originated and pursued at Berkeley. A 500 kV surface contact ionization source has been operated producing a 1 A Cs^{+1} beam. This beam has been accelerated by three long drift tubes pulsed by Marx generators and crowbar spark gaps. The highest energy obtained up to date is about 1.5 MeV with a peak current of about 500 mA. Radial focusing is provided by grids mounted at the ends of drift tubes. The whole system is shown in Fig. 7. Multiple aperture electrostatic quadrupole arrays have been constructed. A short section has been tested in the drift tubes and gave very encouraging results.

In addition to beam and hardware studies using this "4 Joule" system, continuing efforts are devoted to developments of zeolite ion sources, beam diagnostic devices and larger electrostatic quadrupole arrays capable of handling a larger number of beamlets through smaller apertures. Various magnetic materials including the ferritic glass are being tested in connection with designs of induction modules. Theoretical effort is concentrated on the study of effects limiting the transport of high current beam bunches in quadrupole channels.

Design studies are being made for a 50 Joule Induction Linac Test Bed[8]. Produced by a source similar to the existing one the beam is first accelerated by five 500 kV pulsed drift tubes equipped with multiple-beam electrostatic quadrupole focusing. At the end of the drift tubes the 3 MeV, 1 A, 5 μsec beam is injected into a section of induction linac composed of 47 induction modules with <3 mil laminated steel cores and powered by 25 kV pulse forming networks. Radial focusing is supplied by 80 magnetic quadrupoles pulsed by discharging capacitor banks. The possibility of replacing all magnetic quadrupoles by multiple-beam electrostatic quadrupole arrays and/or self-focusing fingers on induction modules are being investigated. Beam compression will be attained by tilting the voltage induced by the modules. The final beam will have an energy of 10 MeV and a current of 3.1 A. Fig. 8 gives a layout drawing of the test bed.

3. Los Alamos Scientific Laboratory

As the lead laboratory for HIF, LASL is responsible for forming and executing the Technical Program Plan. In addition it maintains a limited effort in accelerator development and target design. The accelerator development effort is concentrated mainly on the design and testing of the RFQ structures[5].

4. Brookhaven National Laboratory

The MEQALAC concept was originated and demonstrated here. The most recent effort is on the design and construction of a 200 MHz, 40 keV to 750 keV, 4-beam proton MEQALAC.

5. Lawrence Livermore Laboratory

The total effort is on target design. The design emphasis is to maximize gain and at the same time, ease the requirements on the driver heavy ion beams, in particular that on beam current.

6. Sandia Laboratories

Effort is on the development of a 1 kJ, 4 MeV, space-charge neutralized induction linac[9] (Pulselac C) for protons or carbon ions. Space-charge neutralization is provided by injection of electrons into a magnetically insulated toroidal region. The Pulselac C will also serve as a test bed for neutralized beam transports.

7. Others

In addition to work in major laboratories there are some small scattered theoretical efforts on the studies of beam transports both in and out of the reactor and of reactor design concepts.

R and D Efforts Elsewhere

In Europe there is limited effort in England both at the Rutherford Laboratory on systems studies and at the universities on selected special problems such as the charge exchange cross-sections. The Rutherford Laboratory studies are focused mainly on the rf linac/storage ring approach and has recently produced a 3 MJ, 150 TW system using 8.4 GeV, Bi^{+1} beams[10]. In Germany there is a larger program mainly coordinated by the G.S.I. Laboratories, Darmstadt; both accelerators and pellet physics are being studied. In addition there is a collaborative effort between G.S.I. Laboratories and the University of Wisconsin involving also the Kernforschungscentrum, Karlsruhe.

In Japan, systems studies with emphasis on energy accounting have been undertaken at Nagoya University.

There are indications that studies in this field are being pursued in both the USSR and China, although we have no information on the details of their work.

Acknowledgement

The author is indebted to many of his colleagues, in laboratories both U.S. and abroad for supplying information on their able and interesting work.

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- FUSION
  - MAGNETIC
    - TORUS
      - TOKAMAK (Princeton TFTR)
      - STELLARATOR
      - ASTRON
      - MULTIPOLE
    - MIRROR
      - IOFFE BARS
      - BASEBALL COIL
      - YIN-YANG COIL (LLL TMX)
    - PINCH
      - LINEAR
        - Z
        - θ
      - TOROIDAL
        - Z (LASL ZT-40)
        - θ
  - INERTIAL
    - LASER
      - Nd-GLASS (LLL SHIVA-NOVA)
      - CO_2 (LASL ANTARES)
      - KrF
    - RELATIVISTIC ELECTRON BEAM
    - LIGHT ION (Sandia PBFA)
    - HEAVY ION

Fig. 1 Different categories of devices for fusion energy. Some major devices under construction are given in the parentheses.

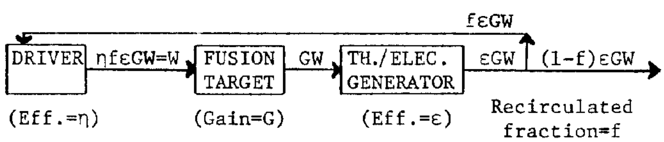

Fig. 2 Energy circuit in a typical inertial fusion electric power plant.

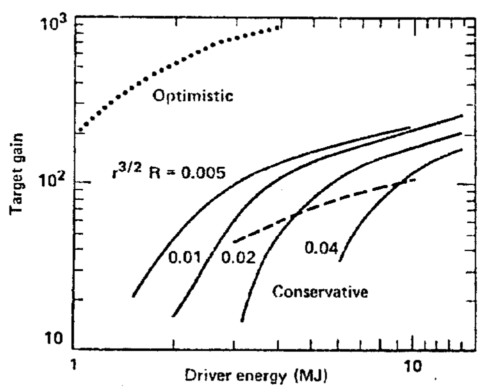

Fig. 3 Gain versus driver energy deposited for the double-shelled target.

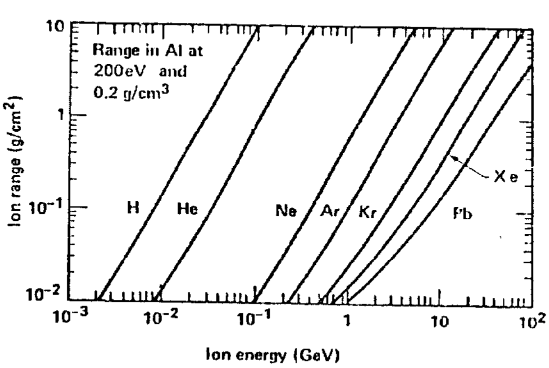

Fig. 4 Range-energy curves for various ions in the target material which is taken to be aluminum at 200 eV temperature and 0.2 g/cm^3 density.

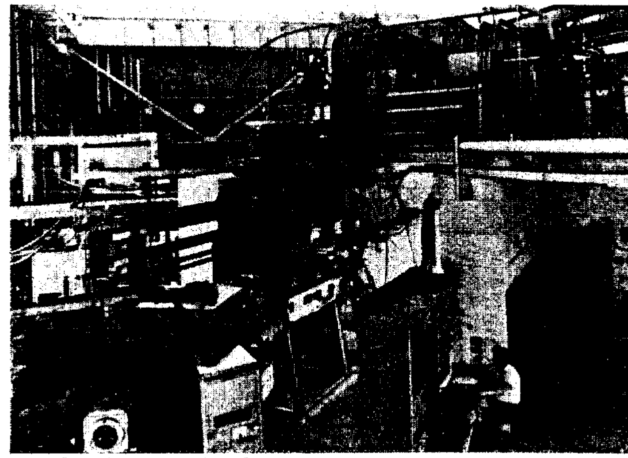

Fig. 5 Photograph of the completed portion of the rf linac/storage ring test bed at ANL. The dynamitron, the Xe^{+1} source and the accelerating column are inside the block-house at the back. Visible in front are the vertical stubs of the three independently phased cavities.

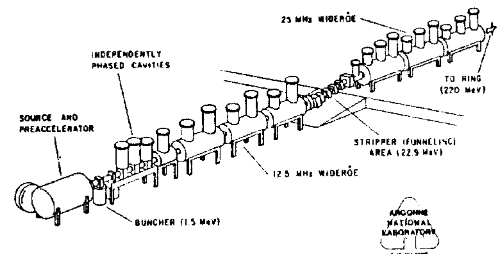

Fig. 6 Isometric drawing of the 220 MeV, Xe^{+8} rf linac for the Argonne test bed - Accelerator Development Facility.

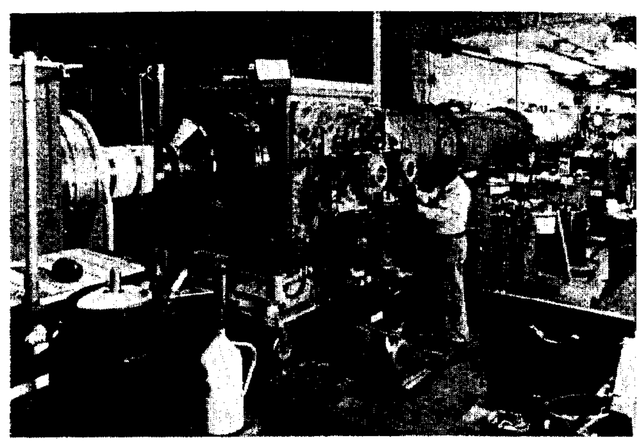

Fig. 7 Photograph of the 4-Joule Cs^{+1} experimental injector system operated at LBL. In the foreground to the left is the contact ionization source in the retracted position. To the right in the back are three sections of tanks containing the pulsed drift tubes.

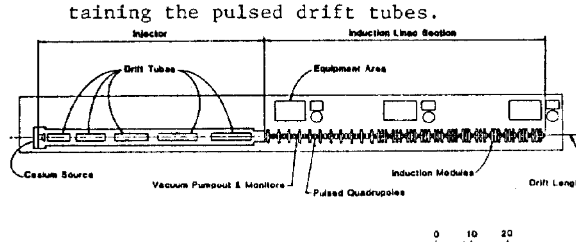

Fig. 8 Layout of the 50-Joule Cs^{+1} induction linac test bed proposed by LBL.