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A REVIEW OF ACCELERATOR CONCEPTS FOR THE ADVANCED HYDROTEST FACILITY*

Alan J. Toepfer
Science Applications International Corporation, Albuquerque, NM, USA

Abstract

The Advanced Hydrotest Facility (AHF) is a facility under consideration by the Department of Energy (DOE) for conducting explosively-driven hydrodynamic experiments. The major diagnostic tool at AHF will be a radiography accelerator having radiation output capable of penetrating very dense dynamic objects on multiple viewing axes with multiple pulses on each axis, each pulse having a time resolution capable of freezing object motion (~ 50-ns) and achieving a spatial resolution ~ 1 mm at the object. Three accelerator technologies are being considered for AHF by the DOE national laboratories at Los Alamos (LANL), Livermore (LLNL), and Sandia (SNL). Two of these are electron accelerators that will produce intense x-ray pulses from a converter target yielding a dose ~ 1,000 - 2,000 Rads @ 1 meter. LLNL has proposed a 16 - 20 MeV, 3 - 6 kA linear induction accelerator (LIA) driven by FET-switched modulators driving metglas loaded cavities. SNL has proposed a 12-MeV, 40-kA Inductive Voltage Adder (IVA) accelerator based on HERMES III pulsed power technology. The third option is a 25 - 50-GeV proton accelerator capable of ~ 10^{13} protons/pulse proposed by LANL. This paper will review the current status of the three accelerator concepts for AHF.

1. INTRODUCTION

X-radiography is a well-known diagnostic for nondestructive test measurements, both of static and dynamic systems. Pulsed x-radiography is commonly used for the study of a number of physical problems involving the hydrodynamics of materials, for example, the stability of accelerated material interfaces and the response of targets to ballistic penetration. Intense, single-pulse x-ray sources have been used for the past 30 years to study hydrodynamic phenomena at the extreme energy densities produced in the hydrodynamic stage of a nuclear detonation (before criticality). Traditionally this data, obtained in non-nuclear tests, has supplemented that available from underground nuclear tests.

With the advent of the Comprehensive Test Ban Treaty (CTBT), assurance of the safety and reliability of the U.S. nuclear stockpile in the absence of underground testing requires the development of high resolution pulsed radiography systems capable of obtaining multi-axis, multi-pulse data in a single dynamic test. The ultimate goal of this Advanced Hydrotest Facility (AHF) is to produce a high-resolution radiographic movie of a dynamic test object. Achievement of this goal requires the development of a number of new technologies including accelerators, converters, beam steering/optics, and detectors which make up the AHF system, as well as the computational tools needed to interpret and visualize the data. This paper reviews accelerator technologies proposed for AHF which are currently under development by the DOE laboratories at LLNL, LANL, and SNL.

2. TECHNOLOGY APPROACHES

There are presently two conceptual approaches to AHF radiography, the traditional x-ray source produced by the interaction of a beam of (12 - 20 MeV) electrons with a high Z "converter" target, and a newer approach using a pulsed beam of (25 - 50-GeV) protons to directly irradiate the test object, which are then imaged by an innovative magnetic lens system. Both approaches must be capable of penetrating the high density test object and achieving the required spatial and temporal resolutions to resolve phenomena of interest. The resulting radiographic source requirements for each approach are given in Table 1.

Table 1: AHF Radiographic Source Requirements

Parameter	X-ray	Proton
Pulse length (ns)	≤ 50	≤ 50
Resolution at object (mm)	0.5 - 1.0	0.5 - 1.0
Equivalent flux - kRads @ 1m - protons/sec	 1 - 2 -	 - 10^{17}
Number of pulses	5 - 10	5 - 10
Number of views (axes)	4 - 12	4 - 12
Pulse separation (μs)	0.2 -15	0.2 - 15
Temporal coverage (μs)	1.5 - 75	1.5 - 75

2.1 X-Radiography Approaches

The U.S. hydrodynamic x-radiography program has traditionally used electron linacs such as the 20-MeV Phermex rf-linac at LANL, and the 18-MeV FXR single-pulse, linear induction accelerator (LIA) at LLNL. For AHF, LLNL has proposed a 16 - 20 MeV, 3 - 6 kA, high repetition rate, solid-state modulator driven LIA, with injector and cavity designs closely related to an advanced LIA being developed for the Dual-Axis Radiography

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Hydrotest Facility (DARHT) now being built at LANL. [1]

An alternate x-ray source based on high current, inductive voltage adder (IVA) technology developed for weapon effects simulation has been proposed by SNL. Pulsed power-based x-ray sources were first developed and have been used extensively by the British Atomic Weapons Establishment (AWE) for hydrotest radiography. These machines have typically been < 10-MeV in energy, but the Sandia-developed IVA technology has extended the capabilities of these accelerators to 20 MeV in the HERMES III accelerator. The IVA AHF proposal is an extension of a pulsed power radiography concept developed as one of the options for DARHT. [2]. For AHF, SNL has proposed a 12-MeV, 60-kA, 50-ns pulse length IVA.

2.2 *Proton Radiography*

Proton radiography may be capable of measuring both mass density and the atomic number of materials in the radiographed object. For AHF, LANL has proposed a 25 - 50 GeV proton synchrotron fed by an 800-MeV linac injector similar to LANSCE. The required beam flux is 5 x 10^{12} protons/pulse. A unique magnetic lens system is used to discriminate between Coulomb multiple scattering and nuclear (strong interaction) scattering effects to extract target information.

3. ACCELERATOR TECHNOLOGIES

In the following paragraphs we discuss the LLNL, SNL, and LANL - proposed accelerators for AHF in more detail, covering the unique features of each, the technology status, and the issues to be resolved.

3.1 *Linear Induction Accelerator (LIA)*

The demonstrated utility of LIAs for pulsed radiography accompanied by advances in solid-state modulator technology have led LLNL to develop the AHF system concept shown in Fig. 1. A 16 - 20 MeV, 3 - 6 kA accelerator produces a MHz train of pulses ranging from 200 ns to 2 μs in length. Fast kickers are used to direct the individual pulses to various beam lines and converters arranged about the object to be radiographed.

Attachment 1

Fig. 1. Schematic of LIA AHF concept.

The Advanced Radiography Machine (ARM) induction accelerator cells are driven by FET-switched modulators. Prototype ARM modulators have been built and tested at LLNL. The 2-MHz, three-stage ARM-II modulator has 4,032 FETs in a series-parallel array and produces a flat-topped 45-kV open circuit voltage pulse with a maximum source current of 4.8 kA. The 10-MHz ARM III modulator, currently under development, will take advantage of the FET's active amplification region to produce arbitrary waveform shapes with a 20-kV open circuit voltage and 7.2-kA output. In both ARM II and III, a separate reset circuit is connected in parallel with the induction cell load.

The LIA fast kicker system concept is shown in Fig. 2. It consists of four stripline electrodes and a fast pulser for driving the electrodes and deflecting the beam. A dc bias dipole wound over the kicker is used to steer the beam in the absence of a pulse to one of two or four desired output positions which are separated by several cm. The pulser drives the stripline electrodes to overcome the bias field and switch the beam to an output position. A drift space following the kicker amplifies the spatial separation, but not the angular separation. A DC septum magnet is used two steer the output beams apart and provide room for additional focusing magnets if necessary. A prototype kicker with two outputs has been installed on the ETA-II beamline at LLNL and preliminary tests give measured deflections consistent with theory.

Attachment 2

Fig. 2. LIA fast kicker system schematic.

Heating of the x-ray converter target by the incident electron beam will cause desorbtion of gas from the target, resulting in plasma formation and ion production which can defocus the incident beam and adversely impact the spot size. In addition shock waves induced in the target by the beam loading can alter the target for succeeding pulses. LLNL is currently investigating several approaches towards alleviating these effects. In one, a retarding potential will be introduced at the target to reduce the accelerating fields produced by the beam and inhibit ion acceleration. An experiment using a modified ATA induction cell will test this concept. For multi-pulse systems, dynamic target concepts have been proposed, both linear (hypervelocity projectile or shaped charge jet) and rotating (flywheel). None of these concepts have been tested to date.

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Two of the major technology issues raised regarding the LIA approach to AHF, namely the reliability of the solid-state electronics in the high voltage environment, and the feasibility of the kicker to maintain beam quality for suitable spot size have been addressed by LLNL in experiments and testing. Proof-of-principle tests have been encouraging. The remaining major issue to be addressed for the LIA accelerator concept is that of maintaining beam spot size at the target and developing a multi-pulse converter concept. The first of these will be addressed on DARHT. The second is the subject of ongoing research at LLNL, LANL, and SNL as part of the overall AHF program.

3. 2 Inductive Voltage Adder (IVA)

The SNL AHF concept is based on multiple modules incorporating the IVA pulse forming network shown in Fig. 3. The ~ 1-µs, 3-MV output from a Marx generator is transformed through three successive pulse sharpening stages to a 1.5-MV, 60-ns pulse driving the cavities. Charging of eight metglas loaded cavities connected in series is synchronized with laser triggered gas switches to give a 12-MV voltage on the coaxial magnetically insulated transmission line (MITL). Electrons which are field emitted from the surface of the center charged conductor are trapped by the self-magnetic field of the current in the line. An ~ 50-ns FWHM, 60-kA electron beam is produced at the cathode.

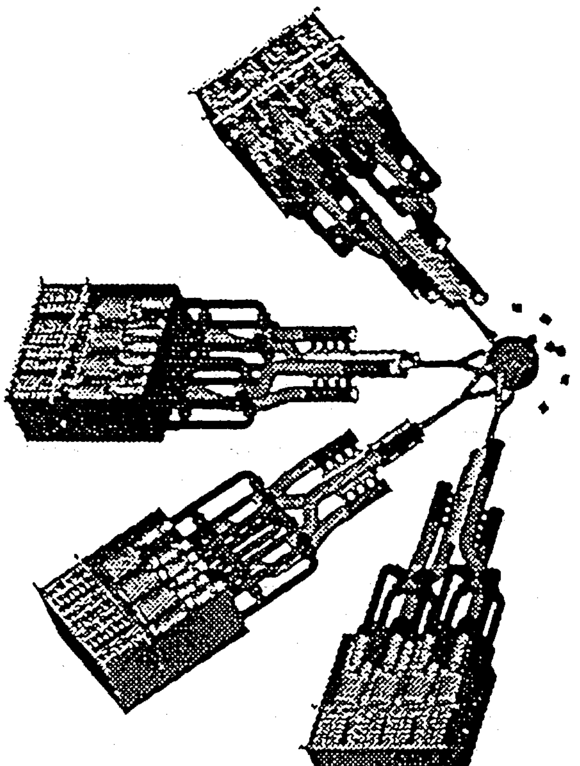

Fig. 3. IVA pulse forming network.

The engineering of IVA accelerators is well in hand, however the physics of the high current x-ray converter diode is complex. Electrons incident on the target are born at the cathode tip. Ions produced by beam interaction with the anode and ionization of neutral gas in the A-K gap stream counter to the electron flow. The diode geometry is designed to inhibit the flow of electrons born with large canonical angular momentum to the anode, and a 60-tesla, axial magnetic field is imposed on the cathode to inhibit the growth of ion hose instabilities in A-K region.

SNL has carried out proof-of-principle experiments at 9.2-MeV, 30-kA on the SABRE accelerator [3], achieving the anticipated 1.5-mm, FWHM x-ray spot. More recently, they have begun scaling experiments on HERMES III at 12 MeV, 150 kA; however, diode contamination on HERMES III caused premature shorting of the A-K gap. From this data summarized in Fig. 4, they have made substantial advances in understanding and modeling the physics of high current "immersed" diodes.

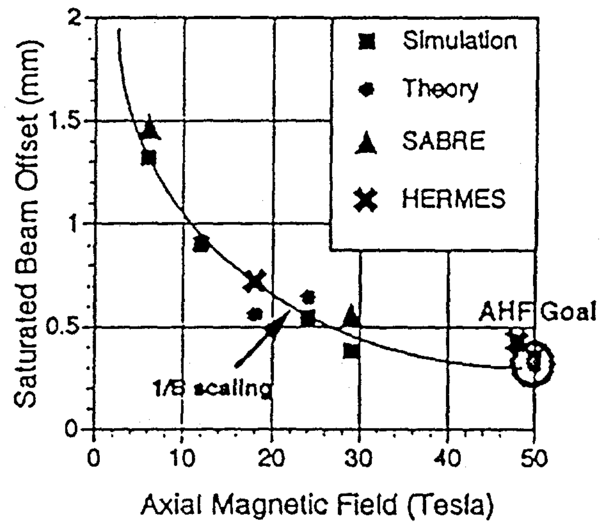

Fig. 4. IVA X-ray spot measurements and calculations.

The major issues confronting the IVA concept are the achievement of AHF parameters in the diode, the feasibility of multi-pulsing a single diode, and the feasibility of charging multiple transmission lines for a multi-axis system. To address the first issue, further experiments are planned on HERMES III. The second issue will be addressed by the construction of a Radiographic Integrated Test Stand (RITS). RITS can be configured to produce either a single 12-MeV pulse or two 6-MeV pulses along the same MITL with complete timing flexibility. The feasibility of splitting and combining pulses in multiple MITLs has been demonstrated in a number of pulsed power machines. Extension of this capability to an AHF accelerator should be straightforward, but is yet to be demonstrated.

3.3 Proton Radiography (PRAD)

The LANL concept for PRAD (Fig. 5) includes an 800-MeV H^- linac injector, a 20-GeV proton synchrotron low energy booster (LEB), and a 50-GeV high energy booster /accumulator (main ring), and is based both on LAMPF technology and designs developed for the superconducting super collider (SSC). A fast kicker modulator extracts the beam from the LEB into the main ring, and a combination of ferrite kickers and electrostatic septum beam splitters transfers the beam bunches from the main ring into ultimately twelve separate beam lines at the test facility. The total number of 50-GeV protons stored in the main ring is ~ 3×10^{12}. An earlier embodiment of this concept which assumed injection directly from the 800-MeV linac into a 50-GeV synchrotron was published in Ref. [4].

Attachment 3

Fig. 5 Proton Radiography Concept

The rf technology assumed in the LANL PRAD concept is 45 MHz at injection (800 MeV), and is raised to 53.3 MHz at the entrance to the delivery system. Based on experience at Fermilab, the proton bunches should be less than 5 ns wide at extraction time, and if properly synchronized, the bunch pattern will be repeated once each 150 ns for as long as beam is delivered to the delivery system. At 800 MeV, a minimum 95% emittance of 4.7 π-mm-mrad is required.

From the requirements in Table I, the kicker modulator must be capable of pulsing up to 120 times on demand over a 1.5 - 75-μs interval. The ferrite kickers would be triode driven and operated with capacitors to make them resonant. Electrostatic septum splitters would be used to divide the beam transversely among two beam lines per stage.

The number of beam lines at the target is currently envisioned to be 8 - 12. Each beamline would transport up to 10 pulses to the target. In order to arrange that the beams all arrive at the target simultaneously, the lines must be equal in length. These long beam lines appear to be the dominant cost driver for the PRAD.

Interaction of the protons with the target occurs via three dominant processes:

- Multiple coulomb (elastic) scattering (MCS) from protons in the target nuclei. The MCS cross section increases with atomic number (A).
- Beam attenuation due to (inelastic) nuclear interactions with protons and neutrons in the target nuclei. The nuclear cross section decreases with increasing A.
- Energy loss due to collisions with target electrons. The cross section for this interaction increases very slowly with increasing A.

PRAD proposes to take advantage of the differing dependence of the elastic and inelastic cross sections on A to measure spatial and time resolved mass density and material composition of the target. To accomplish this, LANL has developed a two stage magnetic lens geometry (inset, Fig. 5) which differentiates between coulomb and nuclear scattered beam particles. [5] Since MCS scattered particles are deflected in the process, it is necessary to refocus them at the image plane following aperture 1. These particles are measured with the inelastic flux at the first detector. The MCS scattered protons are then stripped from the transmitted beam by aperture 2, so that the second detector measures only the beam component attenuated by nuclear scattering. Analysis of these two transmitted beam components should provide data on target mass distribution and A.

PRAD proof-of-concept experiments have been successfully carried out by LANL at 800-MeV on LANSCE and at 7 - 10 GeV on AGS at Brookhaven National Laboratory (BNL). Experiments at LANSCE (Fig. 6) have probed both static and dynamic targets, whereas only static target experiments have been carried out at AGS. A new beam line is currently under construction at AGS for 25-GeV, high intensity tests.

Attachment 4

Fig. 6 Dynamic proton radiographs from LANSCE.

PRAD has the potential to significantly improve the utility of hydrodynamic radiography. The main technical issues associated with the accelerator and beam lines are the demonstration of the kicker modulator, resonant ferrite kicker, and electrostatic beam splitters required to extract and transport the beam bunches to the target. Proof-of-concept experiments must also be carried out at 30 - 50 GeV to demonstrate there are no "unknown unknowns" in the beam-target interaction that could give rise to inadequate resolution, loss of material discrimination capability, or unacceptable background.

The capability to discern material identity needs to be demonstrated. Experiments to date have shown excellent mass density resolution, but do not differentiate materials in the radiographed objects. This capability is a key feature of PRAD.

4. OUTLOOK

Achieving the AHF objective of a high-resolution radiographic movie of a dynamic test object extends the state of pulsed radiographic art well beyond present capabilities. The three approaches to developing a multi-pulse, multi-axis source each have their pluses and minuses. The LIA concept is an extension of existing systems to incorporate modern power electronics, and the IVA technology is an unproven, but potentially lower cost alternative. The major challenge facing these x-ray approaches is the development of multi-pulse converters having the radiation output and spot size necessary to do the job. PRAD is a potentially revolutionary approach which holds great promise for the long term, assuming no "unknown unknowns" are discovered, but may be too costly a system.

The DOE National Laboratories at Los Alamos, Livermore, and Sandia have embarked on a multi-year research and development effort to establish the capability of each approach and are making significant progress. The rate of progress is limited primarily by the availability of funds and facilities. DARHT, when it comes fully on line at the end of 2002, will help to address some of the multi-pulse issues in a real test environment that can only be approximated today.

5. ACKNOWLEDGMENTS

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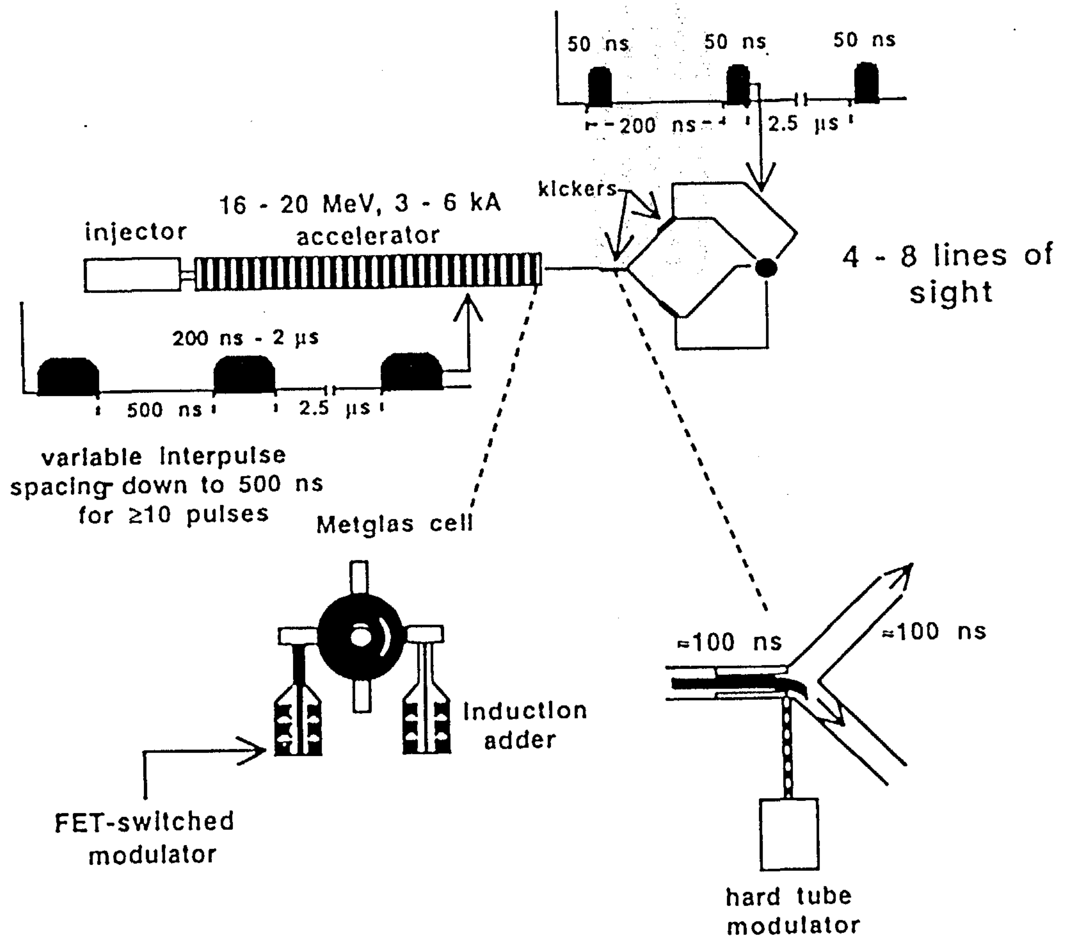
Attach 1

LIA AHF system concept



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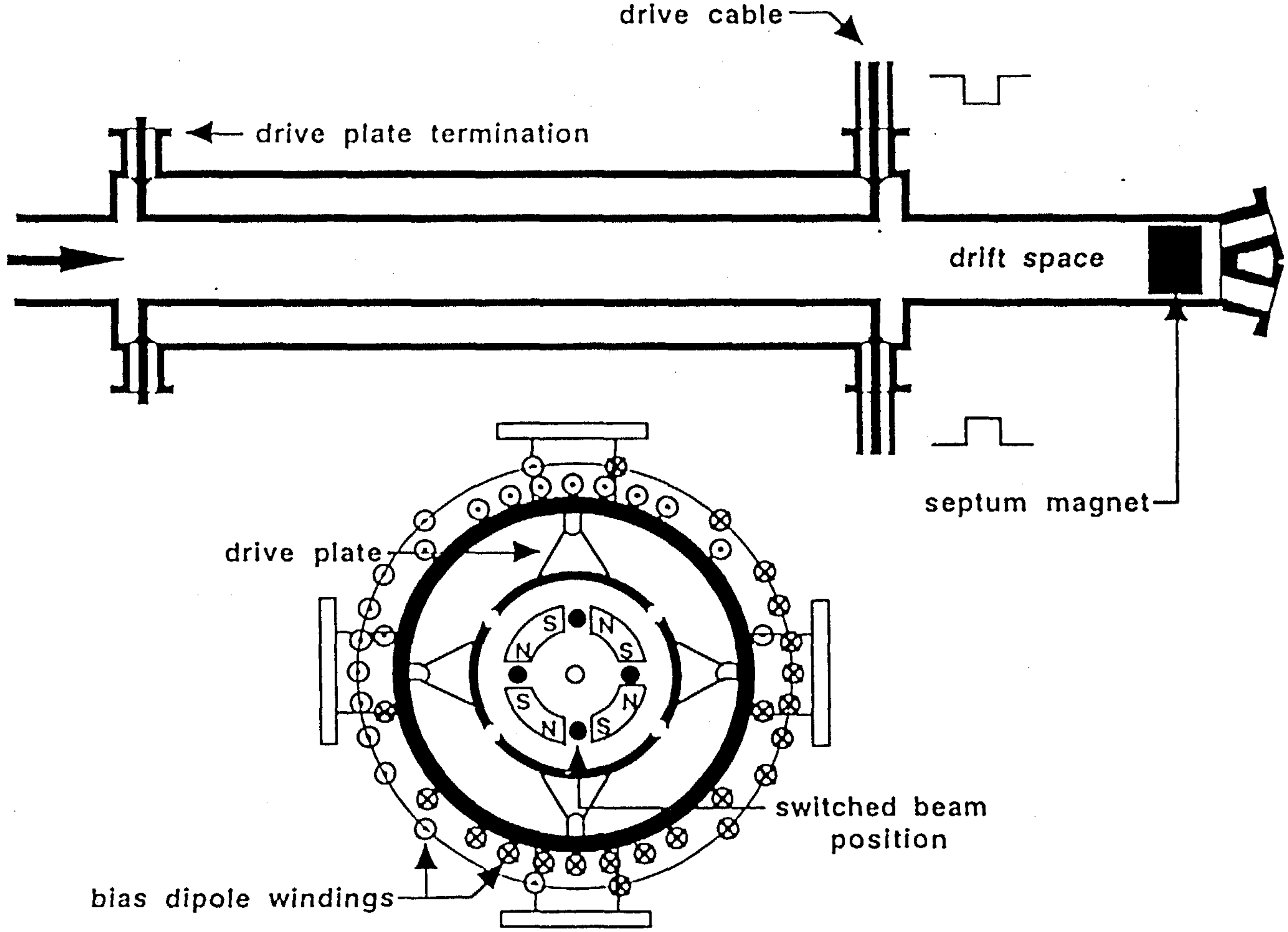
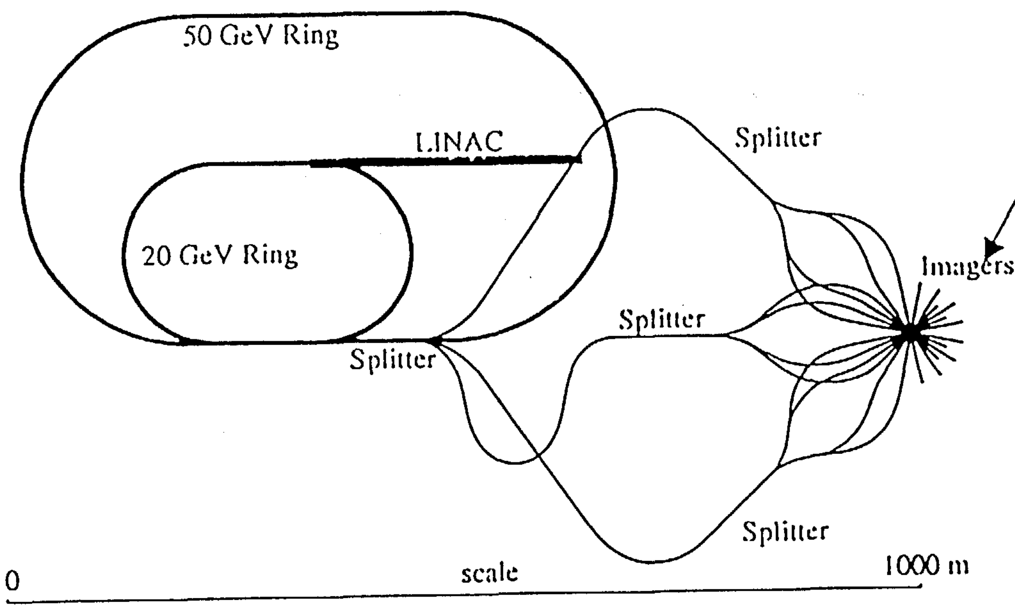
Attach. 2

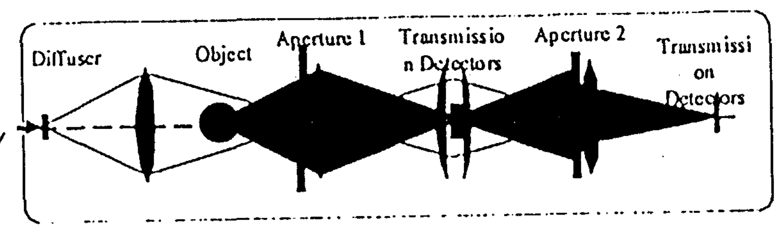
Powering all 4 electrodes allows 4 or more output lines from the kicker



Attach. 3

Conceptual Proton Radiographic Facility





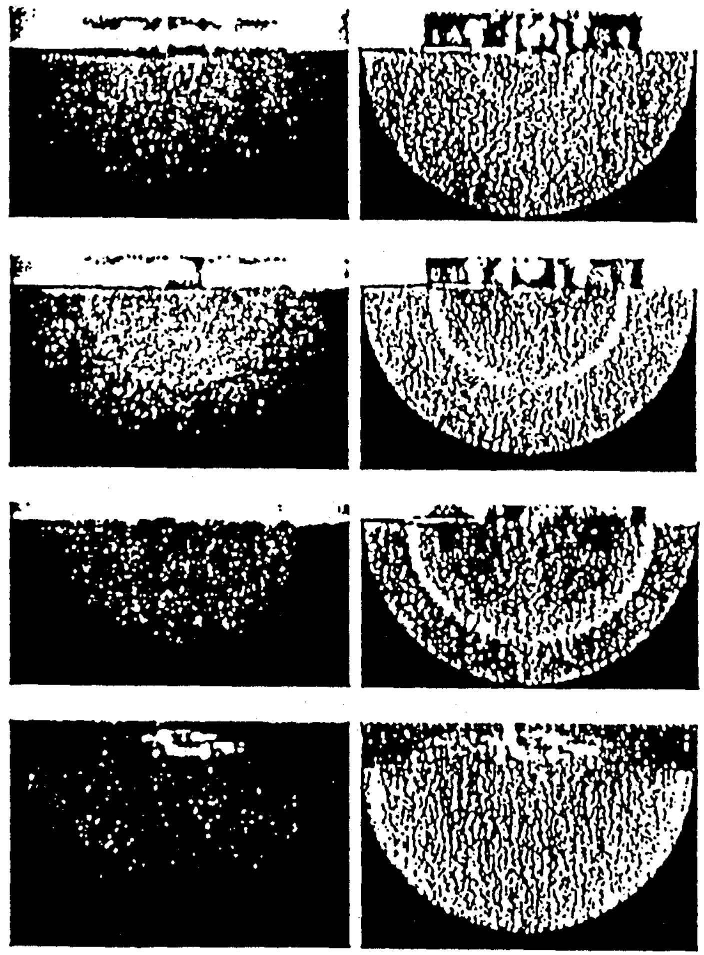
Optical analogy of magnetic lens syste

28~pulses spread out over 75 μsec

Pulse structure in each beamline

Attach. 4

High Explosive Radiographs and Reconstructions with Protons



0.99 μsec

1.90 μsec

2.50 μsec

3.25 μsec