AN INDUCTION LINAC FOR THE SECOND PHASE OF DARHT

H. L. Rutkowski
Lawrence Berkeley National Laboratory
One Cyclotron Road, Berkeley, CA 94720, USA

Abstract

The Dual Axis Radiographic Hydrodynamics Test facility (DARHT) is under construction at Los Alamos National Laboratory. The facility will contain two electron accelerators arranged perpendicular to each other. The second accelerator is a long pulse induction linac using Metglas core technology and will provide a beam pulse at 20MeV with flat top current of 4KA. The focal spot should be less than 1.2mm in diameter. Generation of beam breakup (BBU) and corkscrew motion at the focal spot must be minimal. Very flat beam energy, excellent alignment of transport magnets, and low values for TM mode impedances in the accelerator cavities are needed. The accelerator will consist of a diode injector using a dispenser cathode, providing 3.2MeV energy together with a linac with 88 acceleration cells. Marx generators will provide pulsed power for both injector and linac. The pulse will be transported to a kicker (designed by Lawrence Livermore National Laboratory) which selects four 60ns pulses for transport to the final focus and the conversion target. The status of the design of the accelerator system will be presented along with results from prototype tests. Effect of operational requirements on the design of the accelerator will also be discussed.

1 INTRODUCTION

The accelerator for the second axis of the DARHT facility is a long pulse induction linear accelerator that provides an electron beam that will be used to produce a series of fast high energy X-ray pulses. The fast electron beam pulses, nominally 60 ns in duration, will be chopped out of a 2 μs single pulse and will be transported to a set of X-ray conversion targets. The X-rays will be used to image dense metal objects driven by high explosives. Initially four short pulses are required from the machine though the system could be upgraded to use the remaining part of the long pulse to provide additional views or more time resolution. Lawrence Livermore National Laboratory has the responsibility for the system from the point where the beam exits the accelerator up to the final focus on the X-ray conversion target or targets. The subject of this paper is the injector, accelerator and pulsed power systems that are being designed and built by Lawrence Berkeley National Laboratory.

* This work was supported by the U.S. Department of Energy under Contract No. DE-ACO3-76SF00098.

The injector is a dispenser cathode diode driven by a long pulse Marx generator at 3.2 MV peak flat voltage. The injector beam pulse enters a first cell block of 8 large bore induction cells that accelerate it to 4.6 MeV energy. The rest of the accelerator consists of 10 cell blocks of 8 cells each that accelerate the beam to the full 20 MeV energy. The exit current is 4kA maximum for 2μs. Between each cell block, an intercell provides a pumping point and a station for inserting diagnostics. The entire system is 175 ft. long, from the injector to accelerator exit. The induction cells use Metglas as the ferromagnetic material. The first cell block has a 14” diameter beam pipe while the bulk of the cells have a 10” beam pipe. This is to reduce generation of BBU in the front end. The system is presently in the design stage with prototyping work supporting the design. The injector design is fairly detailed and two options exist for the design of the accelerator cells. A concept of the accelerator sitting inside the building is shown in Fig. 1. The downstream transport and chopper are also shown. The pulsed power units are in an adjacent hall not shown.

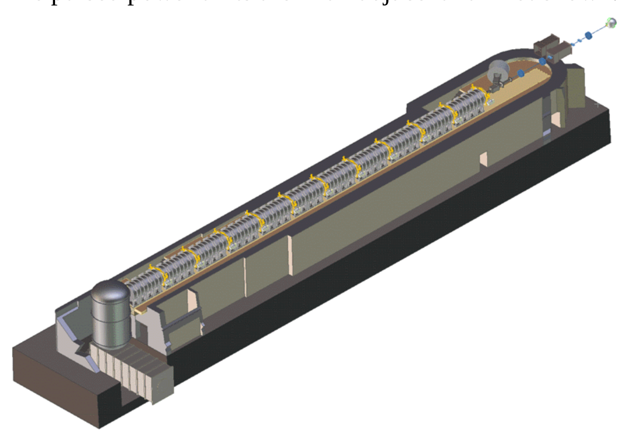

Fig. 1 Accelerator in Second Axis Building

2 INJECTOR

The injector is shown in Fig. 2 together with its first block of 8 cells. The first block of 8 cells is included here because the physics design of these cells is intimately connected with the injector design.

The injector itself is a simple diode designed for rapid acceleration of the electrons emitted by the cathode to 3.2 MeV in order to minimize emittance growth at the start. The emittance required at the final focus at the X-ray converter target is 1500 π mm-mrad normalized. This emittance limit is derived from the 1.2mm focal spot desired at the converter. This spot size is in turn required by the spatial resolution desired in the radiographs. The required maximum flat current is 4 kA for 2.1 μs. However, the current must also be adjustable to allow for operation of the accelerator down to 1 kA to accommodate various commissioning and operational modes. There are a few options for achieving this such as changing cathodes and reducing voltage. The power supply for the diode is a Marx generator being designed by Pulse Sciences Inc. The Marx must provide matched voltage pulses of up to 3.5 MV to the combination diode and ballast resistor load with a flatness of ± 0.5%. The dielectric for the high voltage system is oil and it is being designed to survive a variety of failure modes. The maximum rep rate is 5 shots per minute. The insulator column itself is made of glued Mycalex sections with resistive grading and MOV's for damage protection. The injector is still being designed with fabrication to begin in October 1998.

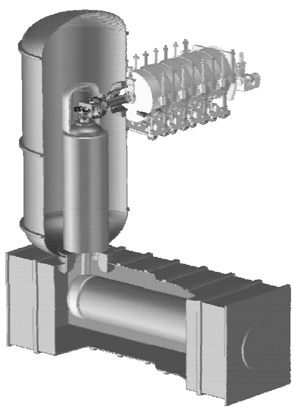

Fig. 2 Injector and First Cell Block

A more detailed drawing of the diode itself is shown in Fig. 3. The cathode is a type M dispenser cathode (8" diameter) which can deliver up to 20 A/cm^2 in a space charge limited mode. The operating temperature will be 1050°C with a uniformity of ±1% across the face. The cathode shroud is partially water cooled near the source and will be made of optically polished molybdenum, stainless steel, or coated stainless steel. Small scale tests on breakdown in vacuum are being carried out on these materials and molybdenum appears to be the best choice so far. However, full size shrouds using all three materials will be tested in the injector. The peak enhanced field stress on the cathode shroud is 162 kV/cm. The shroud material must not only be good to this level of enhanced stress but it must also survive in case of breakdown. Comparison with other machines and the test results so far indicate that the configuration can be made to work at this stress. The plate on which the cathode mounts is attached to a hexapod mounting system that is moved for alignment by six pressure activators. A bucking solenoid can be seen inside this mount in Fig. 3. This solenoid serves to cancel the field at the cathode caused by the focusing solenoids located inside the anode surface. The anode itself is stainless steel and the diode gap is 30cm. As can be seen in Fig. 2, the main current feed from the Marx makes a right angle bend. The vertical part of the feed is 1.5m behind the cathode face. This current feed geometry results in a dipole error field of 3-5 gauss in the diode gap. A quadrupole error field also exists. Correcting coils for these fields are being designed. The sextupole field which could increase emittance was shown to be negligible in calculation as were all higher order fields. A gate valve isolates the diode from the accelerator.

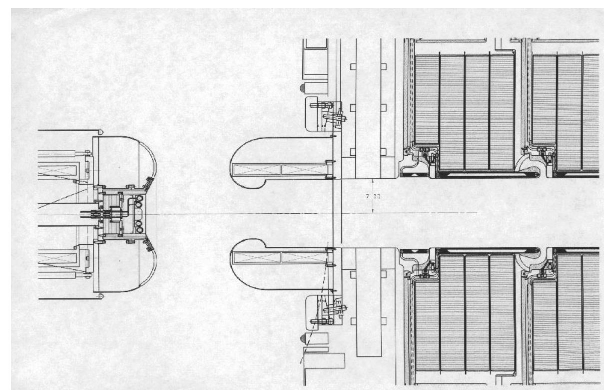

Fig. 3 Diode and First Cells

The rise time of the injector is required to be less than 400 ns and the design point is 200 ns. The fall time is planned to be 100 ns with use of a laser triggered crowbar. The off energy particles produced in the rise and fall must be dumped in a non-destructive way. Conical scapers will be placed in the first 8 cells to remove these electrons. The design of the accelerator cells will be discussed below in the next section.

The insulator column in the injector is designed with a combination of Mycalex insulator rings and high purity aluminum oxide rings. The rings will be glued (Hyso 9359.3) with metal grading rings. The overall height is almost 13 ft. with grading rings and joints. The Mycalex rings were obtained from LANL where they were spares for the column of a decommissioned Van de Graaff accelerator. These rings are 47.5" outside diameter with 3" wall thickness. They offer very large cost savings over building a ceramic brazed column of the same size or a column made of new Mycalex. Mycalex which is a mica-glass mixture seems to be mechanically tougher than ceramic and to have very good breakdown resistance. The clear space inside the insulator column is 38" diameter after the grading resistors (liquid), metal oxide varistors (MOV's) for damage protection, and shock guard rings are in place. Shock guard rings are incorporated to shield the insulator material from any shock waves generated by a breakdown in the oil dielectric. Mycalex is expected to be more survivable than alumina with respect to such shocks.

The original dielectric choice of high pressure SF_6 was discarded for oil because of the fear of insulator catastrophic failure after the column aged and was subject to damage from electrical breakdown. The injector pulse generator is an 88 stage PFN Marx. It can be used to drive different beam currents by varying the resistance of the liquid grading and ballast resistors. The entire high voltage system is being designed to 3.5 MV for safety factor. A laser triggered spark gap is included in the design to reduce unwanted beam in the pulse tail and to aid in shorting the pulse for lower pulse energy applications. The pulse can be shortened in six steps by shorting out PFN stages in the Marx. The design will accommodate diode impedances from 714Ω to open circuit (875Ω nom). A high voltage dome is located at the end of the Marx and contains a hydraulically driven motor generator that provides 15KW power to the cathode dome, power supplies, and diagnostic/controls units to bring information out to the cathode dome. Voltage flatness will be ± 0.5%. The injector Marx and all the accelerator pulsers are required to hold charge for up to one minute to accommodate firing site needs with no more than one failure in 20 attempts. This is an experimental diagnostic requirement. In the experimental shot firing mode the accelerator system cannot fail more than one shot in 600 where failure is defined as detonating the explosive without obtaining beam.

In addition to the design activity there are several testing activities underway. Materials for the cathode shroud are being tested at small scale for field emission threshold, breakdown, and breakdown dependence on vacuum. So far, optically polished Mo has shown the best results with a field emission threshold of 300 kV/cm (200 kV total voltage). Breakdown thresholds above 400 kV/cm have been shown for both Mo and uncoated stainless steel. The breakdown threshold doesn't seem to depend significantly on vacuum between 10^{-8} and 10^{-5} Torr. A scaled version of the injector gun is being set up on the Relativistic Two-beam accelerator (RTA) at LBNL. The RTA machine operates at 1MV total gun voltage, 1.2 kA maximum current, and 0.3 μs pulse length. This test with a 3.5" diameter dispenser cathode will test the beam optics and breakdown at full field stress, current density and in a space charge dominated regime. This scaled gun will be used to test diagnostics and to benchmark the EGUN, IVORY SLICE, and GYMNOS codes that are being used for design to ensure that correct emittances are being calculated. A cathode test stand and a Long Pulse Development Facility are being assembled at LANL to allow testing of full size cathodes and to perform beam tests of accelerator cells respectively. Once the parts for the full injector are ready, the entire system will be assembled and tested as a unit at an industrial location near LBNL prior to being sent to LANL for final commissioning.

Use of a dispenser cathode in the diode dictates an excellent vacuum system and clean servicing environment. The system design calls for three 16" cyro pumps. The design baseline pressure in the tank in 2×10^{-8} t. There is sufficient pumping to reach this pressure in less than 1 hour after roughing.

3 ACCELERATOR

The accelerator must take the 3.2 MeV injector beam up to 20 MeV while not growing the emittance by more than 1000 π mm-mrad normalized. The other major requirement is that the beam at exit cannot have transverse motion of its centroid greater than ± 10% of the beam radius due to all sources. This means both corkscrew and BBU motion. Corkscrew motion of the beam centroid arises because of the misalignment of solenoids in the transport line and energy variations during the beam pulse. BBU arises if transverse magnetic (TM) modes are excited in the accelerating cavities. Since these modes have axial E fields that change direction across the beam axis they can extract beam energy and put it into mode energy. The transverse B field of the mode creates a transverse kick in the beam. In order to reduce corkscrew motion the pulsers for the cells must generate voltage pulses that are flat to ± 0.5%. After the solenoids have been aligned mechanically as well as possible the corrector coils in each cell can be used together with a "Tuning-V" algorithm [1] developed by LLNL to reduce corkscrew motion to a minimum. The voltage for each cell is nominally 193 kV for the small bore cells and 168 kV for each of the first 8 cells. The first block of 8 cells (injector cells) is designed with a 14" beam pipe while the rest of the machine (generic cells) is designed with a 10" beam pipe. This was done because use of a larger bore at low energy reduces the transverse mode impedance in an area particularly susceptible to BBU growth. In a pillbox cavity design the transverse mode impedance scales as [2] w/b^2 where w is the gap and b is the beam pipe radius. Another way to reduce BBU generation besides increasing the pipe size is to increase the solenoid field. However, one cannot arbitrarily increase the transport solenoid field at low energy because it causes emittance growth. The original cell design for the entire accelerator is shown in Fig. 4a

The original 10" cell was designed with a conical section Mycalex insulator. Originally the insulator was to be Rexolite because of the favorable experience LANL has had with this material. However tests at LBNL indicated that it does not survive breakdown from microsecond scale pulses well even though it works very well in the regime below 100ns. Therefore Mycalex was chosen because of its mechanical toughness, good breakdown behavior, and good vacuum properties. A Rexolite insulator will however be tested in the prototype cell. A disadvantage of Mycalex is its high dielectric constant (6.9) which increases the transverse mode impedance of the cavity compared to a Rexolite insulated version. Calculations with AMOS for a cavity without Metglas gave values of 450 Ω/m for the dominant mode. Measurements have been done on a full scale cavity without Metglas and with a cast epoxy insulator of the same dielectric constant as Mycalex. The result for a damped cavity was 330 Ω/m for the dominant mode (TM110). This measurement technique which uses loops to drive modes selectively and probes inserted into the cavity on axis to displace field gives a measurement of Z/Q through interpretation of the frequency shift of a mode due to the probe [3]. This measurement becomes more unreliable as the mode is increasingly damped. Since one wants to damp these modes as much as possible other methods must be used to get definitive results with strong damping. This original cell design is a shielded gap with peak field stress of 100 kV/cm on the negative electrode and 40 kV/cm on the insulator surface.

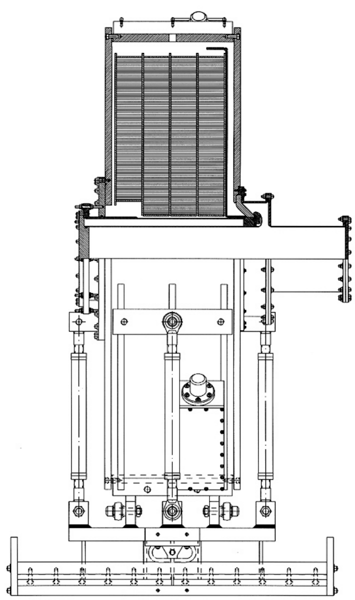

Fig. 4a Original Cell

The process of designing the special cells for the first block led to the design shown in Fig.4b. This design used a different insulator shape and created a space for diagnostics which were desired in the first cells because of the importance of beam motion at the beginning of the machine. Another reason for the change was to create a mode frequency shift between the two types of cells. This configuration will probably be used for the smaller bore cells as well because of the opportunity to place diagnostics anywhere and because of some mechanical design advantages. AMOS calculations give transverse mode impedances of 185 Ω/m at 170 MHz and 170 Ω/m at 450 MHz for this design with a Mycalex insulator and a 14" beam pipe. Applying the same configuration to the smaller bore cells gives 300 Ω/m at 200MHz and 310 Ω/m at 540 MHz. The mode frequencies are shifted between the first block and the rest of the machine which reduces BBU.

Corkscrew motion is combatted by generating flat voltage pulses in the pulsers which are E type Marx PFN's. The transport solenoid fields must also be well aligned to reduce corkscrew. LANL [4] experience in using the Stretched Wire Alignment Technique (SWAT) leads to the expectation of aligning the magnetic center of each solenoid to ± 0.1 mm and the tilt to ± 0.3 mrad. A precise calculation of the final corkscrew motion requires a final machine tune.

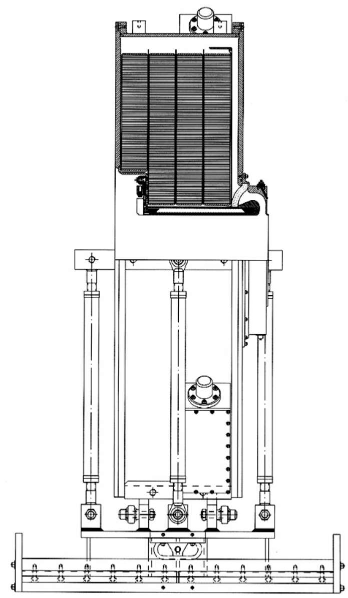

Fig. 4b Injector Cell

The transport solenoids in the generic cells are 12 layer fine wire solenoids 16" long impregnated with epoxy. The 8 injector cell solenoids are only 6 layers thick. The total power for running these solenoids plus the 5" long coils in the eleven intercells is 1.5 MW steady state if each solenoid is at maximum field (0.22T generic, 0.11T injector). The solenoids reside in cavities within the beam pipe and are DC, water cooled units. They float electrically from the machine. PC board type corrector coils are also placed between the solenoid and the pipe wall. An initial tune has been calculated for these solenoids and the beam envelope at exit is 1 cm diameter. Based on the use of the two pipe sizes in the machine, a BBU amplification relative to a straight pipe has been calculated. The values are 12.2 at 170 MHz, and 11.0 at 535 MHz. These numbers are based on a resonant seed at the exit of the injector at the relevant frequency. The amplification is the ratio between the displacement with cavity impedances present to displacement in the presence of continuous beam pipe with no cavities.

The intercells shown in Fig. 1 serve as pumping points with a turbo pump and a cryo pump at each intercell. Design vacuum in the accelerator is 10^{-6} t. The intercells also provide a place for intercepting diagnostics for beam profile and emittance measurement, B-dot loops for beam motion, and beam position monitors.

An important part of the pulsed power design is the Metglas core material. Allied Signal 2605 SC is the baseline design material because of its high ΔB of 2.8T with relatively low drive current. The magnetization current is relatively linear and the short pulse losses relatively low. 2605 SA1 has been tested at LBNL in the unannealed state and is just marginally acceptable. The drive current is very non-linear and the ΔB is about 2.4T. Another candidate is Hitachi Finemet material if it can be obtained at an acceptable cost. The pulser used to drive both types of cells is an E-network Marx PFN. The pulser will feed to the cores at four points to eliminate production of quadrapole fields near the beam. The voltage pulse must be flat to ±.5%. The cell units will be mounted on rails. Removal of a cell requires removal of an intercell to create space for movement. The cells themselves will be capable of individual alignment using a differential screw system developed at the LBNL Advanced Light Source. Each cell weighs about 5 Tonnes. The differential screw system allows accurate movement of such massive structures to 0.001 inches manually. The cells will be vacuum sealed to each other with an inflatable bladder technique.

In addition to RF cavity tests mentioned above, two prototype cells are being constructed. The first uses the original cell design and will be used to measure damped transverse mode impedances and pulsed power tests of breakdown and core compensation. It has SA1 cores. This time Metglas will be in the cell and termination conditions at the outer radius will be realistic. The test cavity had a simple short at the outside. After the coupled loop-probe measurements are performed for comparison with the previous cavity measurements, breakdown tests with Rexolite, Mycalex, and cast epoxy will be performed and the core compensation will be optimized. Finally two wire [5] impedance measurements of the actual damped cell-cavity structure will be performed. The second prototype is a large bore unit that will have SC cores. It will be tested for pulsed power properties and then sent to LANL for beam spill tests. In 1999, 8 small bore cells will be put on the Long Pulse Development Facility at LANL to study beam effects in a full cell block before design of the generic cells is frozen for the large production phase.

ACKNOWLEDGEMENT

The author wishes to thank all the members of the LBNL-DARHT project team for their contributions especially D. Anderson, R. Briggs, E. Burgess, Y-J Chen, S. Eylon, W. Fawley, J. Fockler, E. Henestroza, T. Houck, T. Jackson, C. Peters, L. Reginato, M. Vella, and S. Yu.

REFERENCES

[1] Y-J Chen, Nuc. Inst. Meth. A398, p.139, 1997

[2] G. J. Caporaso, A.G. Cole, Proc. 1990 Linear Accelerator Conf., September 10-14, 1990, Albuquerque, p.281

[3] D. Birx, R. Briggs, T. Houck, L. Reginato, LBNL Eng. Note M7700, July 2, 1998.

[4] J. Melton, Private Communication

[5] L.S. Walling, D.E. McMurray, D.V. Neuffer, HA Thiessen, Nuc. Inst. Meth., A281, p. 433, 1989