6. ION BEAM TECHNOLOGY

The Ion Beam Technology Program (IBT) was formed in 1993 to support diverse activities and applications, all organized around common technology interests. Core expertise includes development and application of ion sources and ion acceleration systems, as well as an understanding of plasmas for use in ion sources and materials modification techniques. This chapter describes selected highlights from among these activities.

During the past year, IBT has significantly extended its involvement in a number of important scientific arenas. We are now actively involved in developing technologies for neutron production, for example, in three main areas. These include our participation in the National Spallation Neutron Source, the Los Alamos Neutron Scattering Center Upgrade, and our own initiative in Boron Neutron Capture Therapy.

We are also continuing to develop technology for the production and acceleration of radioactive ion beams, which will be the US nuclear physics community's first priority for a new facility following completion of the Relativistic Heavy Ion Collider. These efforts include both generic systems which will be needed by any newly proposed facility and specific technologies supporting Berkeley Lab's 88-Inch Cyclotron and the ISAC radioactive beam facility now being built at TRIUMF.

In addition to our considerable ion source and plasma test stand resources, we have developed a low beta test stand for testing and evaluating (with beam) radiofrequency quadrupoles and other rf structures essential to the efficient manipulation and acceleration of radioactive ion beams. A cw rf amplifier for use on the test stand, adapted from a unit that was used in the SuperHILAC Third Injector, is now nearing completion; it will be capable of powering such structures in the range of 12–36 MHz.

During the past year, our various activities have also achieved a much greater degree of cohesiveness and synergy. This is especially true in the creative use of ion sources and plasmas for ion beam formation and materials modification. Several new materials synthesis techniques have been developed with direct benefit to accelerator R&D efforts, including our own RFQ program. In addition, plasma techniques aimed at enhancing ion species concentration and at rapid pulsing in the beam formation process found uses in boron neutron capture therapy (BNCT), radioactive ion beams, fusion energy, and the National Spallation Neutron Source (NSNS).

Another example of the synergy among our seemingly disparate programs is titanium nitride coatings, often used to elevate the work function of materials to reduce unwanted production of electrons in storage rings and rf cavities. We have

assisted PEP-II in a consultant role and in developing options for coating long, irregularly shaped chambers. These techniques are also of interest to the Proton Storage Ring at Los Alamos and to the NSNS.

The BNCT initiative has received initial DOE funding and, following an outstanding review this year by a high-level DOE-appointed panel, we are poised to ramp up our efforts next year toward an accelerator-based clinical facility to be sited here and operated in partnership with the University of California, San Francisco (UCSF). This effort combines AFRD expertise in the IBT and Fusion Energy Programs; biology and imaging expertise in Berkeley Lab's Life Sciences Division; and clinical expertise from UCSF, Stanford and other major West Coast medical schools.

We have also taken the lead coordinating role in a new AFRD project with Los Alamos National Laboratory (LANL). This effort is expected to lead to significant participation by Berkeley Lab in the design and construction of a second axis for LANL's Dual Axis Radiographic Hydrodynamic Testing facility, or DARHT. This requires coordination of a broad base of resources, mostly from the Fusion program and the Engineering Division.

Our most important goals for the coming years are the successful completion of our commitments to other major projects, such as NSNS and LANSCE Upgrade; consolidation of a role in the support of radioactive ion beams facilities together with Berkeley Lab's continuing nuclear physics activities; and the successful launching of new initiatives such as BNCT and DARHT. In addition by working in cooperation with TRIUMF, we see a significant opportunity to expand our work with radioactive beams by developing new rf and diagnostic systems that will be needed for a future US Isospin Laboratory facility and that can be installed and tested at ISAC.

Reported by Richard A. Gough, Program Head

A High-Duty-Factor Front End for the NSNS Linac Injector

One of the most significant events in the IBT Program last year was the selection of LBNL to design and produce the front end of the National Spallation Neutron Source (NSNS) linac injector.

The NSNS comprises a 1- to 4-MW H^- linac injecting one or two full-energy storage rings. The proton beam is extracted in one turn from the storage ring and

transported to a heavy-metal spallation target, where neutrons are produced for the users' beamlines. Oak Ridge National Laboratory carries overall responsibility for the administration of the project. Berkeley Lab and the Los Alamos, Argonne, and Brookhaven National Laboratories are responsible for various subsystems.

Berkeley Lab has the responsibility of designing and producing the “front end,” which includes the H- ion source, the Low-Energy Beam Transport system (LEBT), Radio-Frequency Quadrupole (RFQ) accelerator, and the Medium-Energy Beam Transport system (MEBT). These roles build on AFRD's legacy of successful design and construction of similar systems.

Background

The RFQ accelerator development program here started in 1981, resulting in the development of one of the first highly successful heavy-ion RFQs, which was used in the new light-ion injector for the Bevatron. This RFQ was followed shortly by another, constructed in collaboration with an international group including CERN, Grenoble and GSI. It was to serve for many years as the heavy ion injector to the CERN Proton Synchrotron and Super Proton Synchrotron, where it played a part in the highest-energy interactions achieved as of that time in the SPS storage ring. The Bevatron RFQ and the CERN RFQ therefore played key roles in launching the new field of relativistic heavy ion physics. LBNL then produced a proton RFQ that replaced the Cockcroft-Walton proton injectors at Brookhaven. All of these RFQs were of the same basic design, operating at 200 MHz. The next step was a 400-MHz RFQ with an innovative mechanical design, which was much more economical to produce than existing RFQs because it was self-aligning and meant from the outset for mass production on numerically controlled machine tools.

In the meantime, interest grew here in perfecting an all-electrostatic acceleration column that would be compatible with the volume-production ion sources that had reached such a high state of development here. A first attempt with the SSC injector was promising, but further development was indicated. We went on to develop a double-einzel all-electrostatic accelerating column whose measured beam characteristics agreed very well with extensive code-based predictions. When coupled with the 400 MHz RFQ, it worked as predicted (Figure 6-1), showing that the difficult problem of matching it into an RFQ could be successfully solved.

Thus three areas of expertise pioneered for the Bevalac (since decommissioned) and for magnetic fusion energy—the ion source, RFQ, and electrostatic quadrupole accelerating column—combined to make Berkeley Lab the logical choice to develop the NSNS front end.

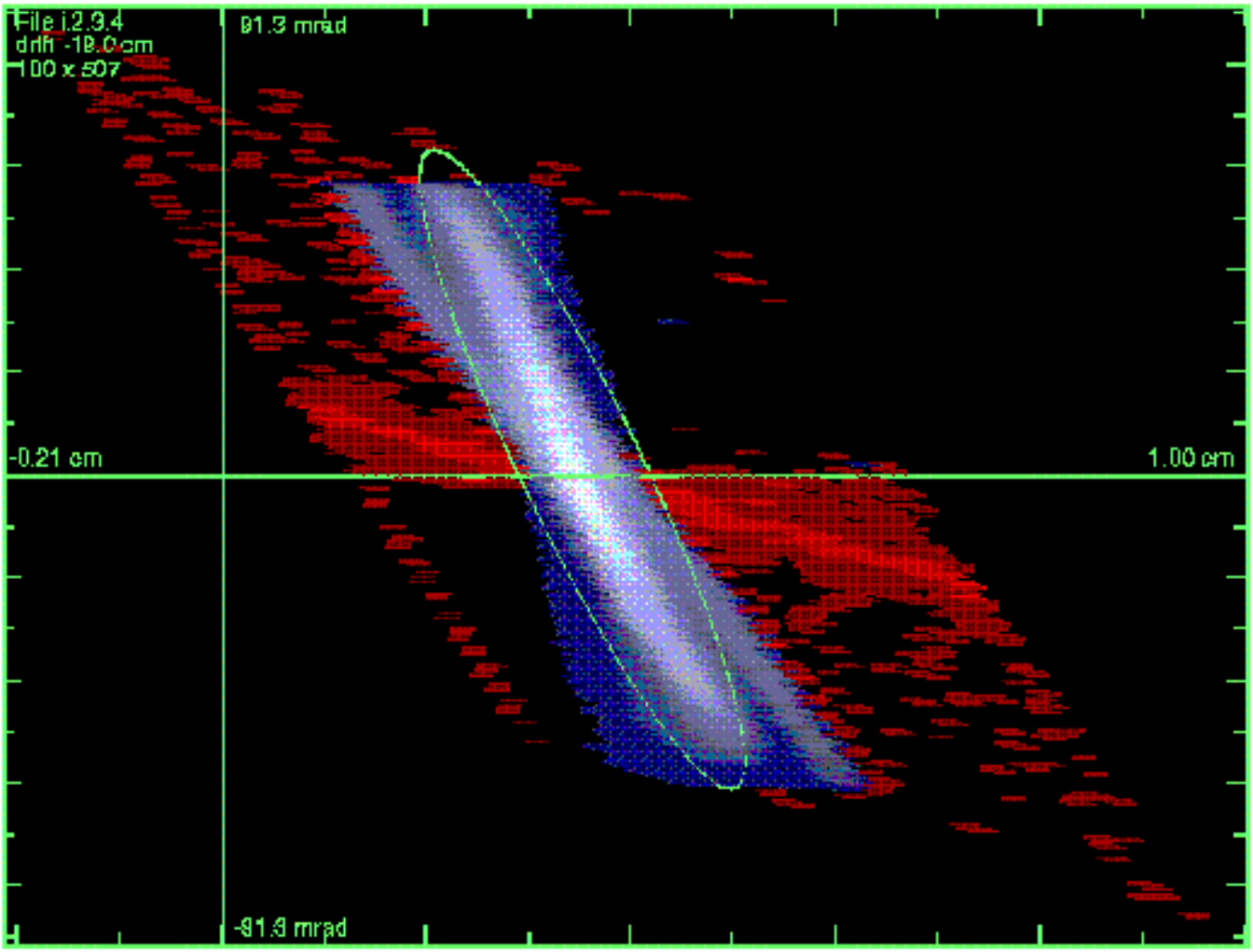

***Figure 6-1**. Measured beam phase space at the end of the 40 keV accelerating column in our experimental facilities. The ellipse is the RFQ acceptance ellipse shape (but not size).*

NSNS Front End

Table 6-1 lists the interface definitions that the front end must satisfy when injecting into the rest of the linac, supplied by Los Alamos. The values are for the baseline 1-MW specification and the 2- and 4-MW options. The 2 MW option calls for doubling the 28 mA to 55 mA, and the 4 -MW option doubles the front end equipment to the 20 MeV point, and combines two front ends with an rf funnel.

***Table 6-1**. Front-end parameters.*

Ion	H^-
Energy	2.5 MeV
Current	28 (55) mA
Bunch frequency	402.5 MHz
Pulse length	1.1 ms
Repetition rate	60 Hz
Duty factor	6.1 Percent
Transverse emittance	0.15 (0.2) pi mm-mrad, rms, normalized
Longitudinal emittance	0.090 (0.120) MeV-degrees, rms
Chopper frequency	1.188 MHz

The challenges for the front end design are the 6.1% duty factor, critical for the ion source and the RFQ, and the physical length of the RFQ, about five free-space wavelengths.

Our technical approach to the front end design is to divide it into four main areas of development: ion source (reported elsewhere in this chapter), LEBT, RFQ, and MEBT. In addition, important global areas of interfacing with equipment produced at other laboratories, integrating instrumentation and control, and conventional facilities also receive strong attention.

NSNS Front-End Technical Components

The beam dynamics design of the front-end systems is essentially complete, and the mechanical and electrical design is just entering detailed engineering development. Here is our best view of the completed design at this time.

Low-energy beam transport system (LEBT)

The injector linac system injects the storage ring with about 1000 turns of beam, using H- injection. After the ring is filled, the circulating beam is extracted in one turn. To provide a notch in the circulating beam for the extraction kicker to rise without unwanted beam to target the extraction septum magnet, the injected beam is chopped at the 1.188 MHz ring revolution frequency, with an on-beam duty factor of 65%.

To satisfy the requirement that “dark current” (in the middle of the off-period of he beam) must be low, three tandem choppers are used—one each in the ion source, LEBT, and MEBT—

with the latter choppers providing faster rise/fall time. Transport of a chopped beam from the ion source requires unneutralized transport.

Accordingly, the LEBT (Figure 6-2) is an all-electrostatic accelerating device, with the beam initially extracted from the plasma chamber in an 81-kV, 39.5 kV/cm gap, followed by two einzel focusing lenses whose potentials are 10 and 15 kV lower than the 65-kV body potential of the ion source. The 35 mA H- current for the 1 MW design (twice that for the 2- and 4-MW options) is separated from the electron background in the first gap by permanent magnets. The double-einzel focusing system matches the round beam into the acceptance of the RFQ.

A unique feature is the division of the two einzel lenses into quadrants, where transverse steering fields are introduced, producing up to +/-25 mrad of angular steering. The entire LEBT, with the ion source an integral part, is also mechanically movable by +/-4 mm for transverse steering into the RFQ. A set of eight low-friction pads supports the entire atmospheric pressure, and a single sliding O-ring isolates the vacuum.

The second beam chopping station is implemented in the LEBT by applying deflecting voltages to the split einzel lens quadrants, with the deflected beam targeting an aperture stop at the RFQ entrance. The beam is alternately deflected to four different locations, lowering the average power dissipation of each location to 10 watts or lower, depending on the effectiveness of the ion source chopping.

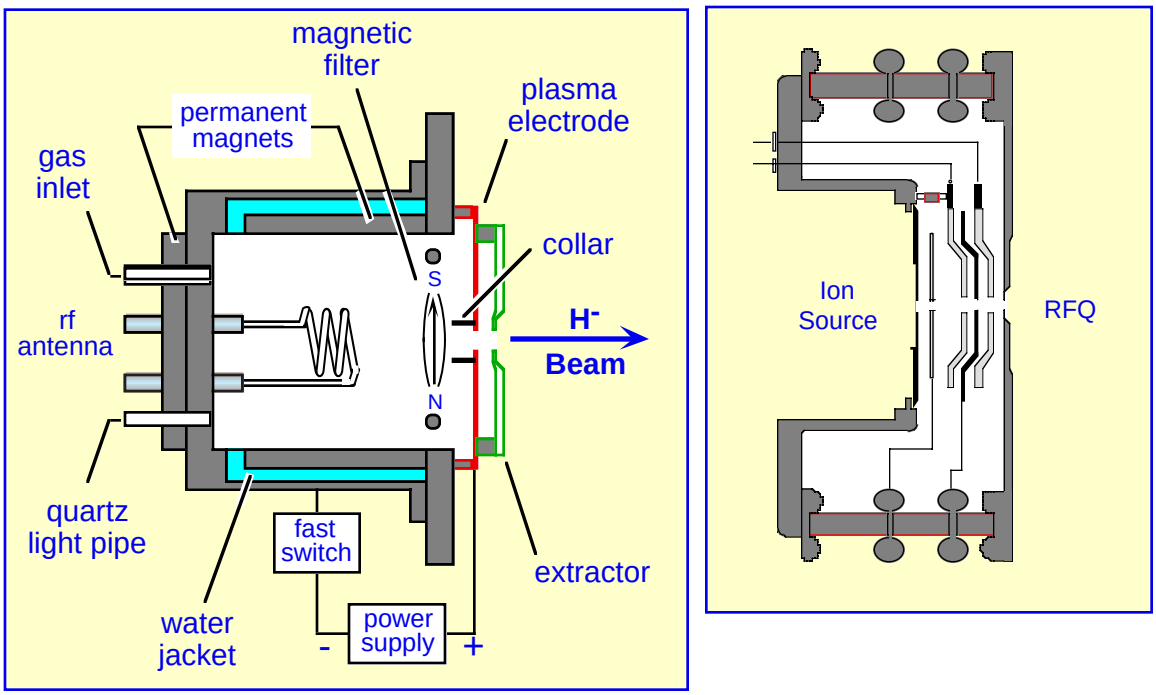

Figure 6-2. *The ion source (left), LEBT, and RFQ are among our contributions to the NSNS front end. We are also designing the MEBT. The beam dynamics work is essentially complete; we are now working on detailed design, fabrication, and, in some cases, testing.*

The LEBT design follows very closely a similar design built recently at LBNL [Staples et al., Linac94 and Linac96] The agreement between the simulated performance and the measured performance was excellent, including matching into the LBNL 400 MHz RFQ and subsequent acceleration.

Radiofrequency quadrupole linac (RFQ)

The RFQ accelerates the H- beam from 65 keV to 2.5 MeV with a duty factor of 6.1%. Various aspects of RFQ performance--in particular, transmission, emittance preservation, and low longitudinal emittance--must hold up over the current range of 28 to 55 mA.

The RFQ operates at 402.5 MHz and is 3.7 meters long. The physics design is quite conventional and is well within the bounds of conservative design practice. The low longitudinal emittance of 0.12 pi MeV-degree, rms, is the result of a rather long buncher section. The peak electrical field at the vane tips is limited to 34 MV/m, or 1.75 Kilpatrick. The two major challenges are the 6.1% duty factor and the great length (5 free-space wavelengths).

The technical solution to the RFQ mechanical design calls for the RFQ to be fabricated in four modules and bolted together with a soft metal conformal gasket. Each approximately 0.9-meter-long module comprises four sections, brazed together longitudinally, with self-aligning assembly features machined into the individual sections, which include the RFQ body as well as the vane tip region.

At full gradient with 55 mA of beam, the rf power requirement is 667 kW, and the maximum power density on the outer wall is 1.7 W/cm^2, with some hot spots near the vane cut-outs at the ends of the RFQ.

To insure a better than 0.002 inch tolerance after three brazing cycles, the RFQ will be constructed of Glidcop AL-15 material, with brazed surfaces prepared to be compatible with silver-bearing braze compounds. The bolt-together flanges joining the four modules and the end plates will also be formed of Glidcop.

Water cooling passages will be gun-drilled from each end of each modules, with the ends then plugged and additional water passages drilled radially. The thermal design of the RFQ results in no more than a 3° C temperature variation in the body of the structure, resulting in a frequency shift from power-off to power-on of less than 0.025% and a peak material stress of less than 1200 psi, which will prevent any stress cracks from developing due to continued thermal cycling.

An RFQ that is 5 free-space wavelengths long requires rf mode stabilization. Assembly tolerances alone cannot prevent mixture of the TE_{120} quadrupole mode with undesired TE_{11X} dipole modes, which result in beam steering and loss. The vane coupling rings (VCRs), invented at LBNL and used on all previous RFQs, will be replaced here by the easier-to-cool pi-mode stabilizers, developed and demonstrated successfully for the Japan Hadron Collider RFQ at KEK.

Further materials tests for vane tips and brazing techniques will be carried out at LBNL with a high-power test program, starting soon. In addition, detailed cavity geometry will be selected on the basis of a cold-model program, where the geometry to produce the exact resonant frequency will be determined, and the pi-mode stabilizers will be optimized.

A full-scale prototype RFQ will be built and tested at LBNL, with beam, before a final production RFQ is built. The prototype will be used temporarily at ORNL to help commission the first part of the linac, produced by LANL, before the final RFQ replaces the prototype.

Medium-energy beam transport system (MEBT)

The MEBT's main function is to provide room for the final 1.188 MHz beam chopper. This chopper, provided by LANL and incorporated into the MEBT, provides the 2.5–5 ns rise/fall times necessary for beam transport in the rest of the linac and the linac-to-ring transport system. The rest of the MEBT components match the beam from the RFQ through the choppers and thence into the DTL, provided by LANL.

The primary beam dynamics issue is to reduce the emittance blow-up that occurs in the MEBT due to the nonlinear space charge forces of the 2.5 MeV beam with a 8.8 rms degree phase width. The solution is to provide strong transverse focusing and to keep the MEBT short.

Effects of mistuning, which include tune depression due to space charge, are minimized if the transverse focusing phase advance of a strong focusing system is not allowed to vary quickly along the beamline. Accordingly, the rapid phase advance in the RFQ is adiabatically slowed down by six closely spaced magnetic quads in the entrance section of the MEBT, with an rf rebunching cavity placed after the fifth quadrupole. This quad sequence also optimally matches the beam through the first 0.5-meter-long traveling wave chopper, with a waist in the center of the chopper in the transverse plane, and a waist at the exit in the deflection plane, which maximizes the ratio of beam deflection to beam size. A second rebunching cavity is located in the center of the beam line, which is the symmetry point of the MEBT. An antichopper mirrors the chopper, so that the effects of undesired but always present ringing do not produce angular deviation of the beam as it enters the DTL.

The present MEBT design is 3.69 meters long, with 18 quadrupoles and three rebuncher cavities. For the 1 MW scenario, the transverse emittance increase is significantly less than 10%, with no increase in longitudinal emittance.

Overall Collaboration

LBNL has a history of highly successful multilaboratory collaborations. We expect this one to be no exception. ORNL is giving each laboratory free rein in choosing the appropriate technology, and the coordination of interfaces and commonality of equipment is handled well through frequent all-group meetings. The interfaces between systems, such as ion source-LEBT, MEBT-chopper and MEBT-DTL have now been established. Areas of commonality, such as rf transmitters and instrumentation and control equipment, are being fine-tuned. We are now entering a period of R&D engineering development and subsequent cost refinement in preparation for the preparation of a comprehensive Conceptual Design Report.

Reported by John Staples

Ion Source Development

The Plasma And Ion Source Technology Group performs R&D in four different areas: ion source development for neutron-source, industrial, and nuclear-science applications, plus plasma technology for Accelerator and Fusion Applications. Below are some highlights of recent work in these areas.

Ion source development for neutron sources

We have been contributing to the National Spallation Neutron Source design effort that was described earlier, and have also been putting our ion-source expertise to work by improving miniaturized commercial devices called “neutron tubes” that are used for subsurface characterization in the environmental field.

Volume H^- source development for the NSNS

We are participating in the design of the National Spallation Neutron Source, a project which involves five DOE laboratories: LBNL, LANL, BNL, ANL and ORNL. The IBT Program is responsible for the design and fabrication of the front- end section of this 1 MW neutron source, which includes the ion source, LEBT, RFQ and MEBT. In order to meet the tight project schedule, we started the ion source R&D in mid-1996. For this purpose, we refurbished Test Stand 11 in Building 16 and the old RF-driven “volume-production” multicusp H^- source that was the prototype for the one in the Superconducting Super Collider.

The initial goal is to accelerate 35 mA of H^- ions with normalized rms emittance of 0.15 π-mm-mrad and a duty factor of 6% (1 ms pulse length and 60 Hz). To date, we have achieved 15 mA of H- current at 6% duty factor and at 22 kW of RF power with pure hydrogen discharge. A new RF power supply with output power higher than 50 kW and a new matching box have been purchased. With this new power supply, and operating the hydrogen discharge with cesium, we expected that the H^- current can be increased to 70 mA (which is required in the 1- and 4- MW NSNS upgrade options).

In order to meet the 6% duty factor requirement, we have improved the design of the collar and cesium dispensing system in the new NSNS prototype source. Instead of dumping the extracted electrons onto the second electrode with high impact energy, we will deflect them back to the first electrode. The permanent magnet arrangement on the exit aperture as well as the H- ion beam optics are being investigated with both 2-D and 3-D computer codes. Previous studies demonstrated that it is possible to pulse an H- beam at the ion source. For this purpose, a fast electronic switch capable of producing 500 ns (+80 V) pulses on the first or plasma electrode has been installed on the RF-driven multicusp source. Preliminary results demonstrated that fast beam switch-off time in the order of 100 ns or less is achievable.

Surface-conversion H- source development for the LANSCE upgrade project

The LANSCE facility (Los Alamos Neutron Scattering Center), based on the Los Alamos Meson Physics Facility (LAMPF) accelerator, is going to be upgraded to a 200 kW spallation neutron source. The IBT Program has a collaborative agreement with LANL to improve the H- output current from the source from 20 mA to 40 mA while maintaining approximately the same emittance, reliability, and lifetime of the source. Over the past six months, we have installed

and operated a surface-conversion H- ion source. We have successfully reproduced the results of the LANSCE source using filament discharge. Currently, we are trying to improve these results by installing two extension chambers equipped with magnetic filters. The plasma in the source chamber can be generated either by filament dc discharge or by RF induction discharge. If the operation is successful, we are planning to design and construct a toroidal double plasma chamber system for the LANSCE upgrade project.

Ion source development for neutron tube applications

The IBT Program is currently developing a compact, RF-driven, pulsed ion source for neutron generation. RF-driven ion sources have thus far found numerous applications ranging from particle accelerators to ion implantation systems; they should be outstanding for neutron tubes in any application where sufficient rf power can be conveyed to the source. They are simple to operate, have long lifetimes, and provide high density plasmas with high monatomic hydrogen ion species yield; these characteristics make the RF-driven source a viable candidate for the next generation of compact, high output neutron generators. An attempt has been made to miniaturize the RF-driven ion source and the necessary impedance matching network to fit in a 5 cm diameter borehole with the goal of producing 10^9 to 10^{10} D-T neutrons per second. Typical operating parameters are: repetition rates of up to 100 pps with pulse widths between 10 and 80 μs, and source pressure as low as ~ 5 mTorr, which is critical to avoid high-voltage break-downs in the 100 keV accelerator columns. In this configuration, peak hydrogen current densities exceeding 1.18 A/cm^2 with an H^+ ion species yield over 94% have been extracted from a 2 mm diameter exit aperture.

Ion Sources for Nuclear Science Applications

The group's tradition of applying its expertise to the needs of the nuclear-science community continued in 1997. Various types of ion sources are suited, respectively, to generating extremely pure beams of singly-charged ions (the multicusp, volume-production source) and to generating highly charged ions that can be driven to higher energies with a given accelerator—the Electron Cyclotron Ion Source (ECRIS) and Electron Beam Ion Source (EBIS) technologies.

Multicusp Ion Source for Radioactive Ion Beam Production

In collaboration with the Nuclear Science Division, we have developed a 13.5 MHz RF-driven multicusp source for radioactive $^{14}O^+$ ion production. This unit will be used as part of an integrated target / ion source system now under development for a radioactive ion beam experiment to investigate the mass of the neutrino. ^{14}O will be generated in the form of CO via the $^{12}C(^3He, n)^{14}O$ reaction using a 3He beam from the 88-Inch Cyclotron. Neutral radioactive CO will be transferred via a gas tube into the multicusp source chamber, dissociated, ionized, accelerated, and implanted into a carbon target which is analyzed in a beta spectrometer within the 70 s lifetime of ^{14}O. Since the amount of radioactive CO produced will be very small, the ion source discharge will be mainly formed by a background argon gas. Ion source characteristics using H_2, Ar, and Xe gas and a 90% Ar + 10% CO gas mixture for generating the discharge plasma have been studied during the past year. Source parameters such as extractable ion current, ion species distributions, gas efficiency, axial energy spread and beam emittance have been measured.

Experimental data show that CO molecules can be dissociated efficiently in the ion source at RF input power levels above 1500 W. In addition, gas efficiencies of 60% for argon and 80% for xenon have been obtained. A relatively low axial energy spread of 2 to 3 eV for the filament driven source and 4 to 7 eV for the rf driven source have been observed. The same ion source unit has also been tested with hydrogen discharge. In the presence of a hot molybdenum liner in the source chamber, atomic H+ ion percentages higher than 90% have been achieved with a RF input power greater than 2 kW, making the ion source also useful for intense proton beam production.

The design and construction of the ion extraction and transport system for the radioactive ion beam line is in progress. A new test-stand dedicated for source and beam transport study is now under construction in Building 5. Once completed, we can measure the gas hold-up time for oxygen in the source, the transmission of the LEBT system as well as the mass distribution of the ion beam.

Electron Cyclotron Ion Source (ECRIS) and Electron Beam Ion Source (EBIS) Development

An ion source to study the production of medium charge state ion beams for the nuclear science program has been developed. A single-stage 2.45 GHz electron cyclotron resonance ion source design has been chosen for this application In order to improve the ion confinement time, the 2.45 GHz ECRIS features an enhanced axial magnetic field (for high mirror ratio) and a strong radial hexapole field produced by a novel Nd-Fe-B permanent magnet configuration. The source plasma volume is much larger than conventional sources while still maintaining a high mirror ratio. The magnetic field configuration also allows coupling of higher frequency microwaves into the source, enabling us to compare source performance at 2.45 GHz and 6 GHz in the future. The ECR ion source test-stand currently under construction consists of the following components: ion source, diagnostic spool (faraday cup and emittance scanner) and beam transport system (quadrupole triplet and analyzing magnet). Ion beam parameters such as beam emittance, current density, charge state distribution will be measured. The planned research program will be focused on the improvement of beam extraction from an ECR ion source with respect to applications for the nuclear science program and MeV ion implantation systems.

In parallel with ECR ion source development, experiments are in progress to develop a high current laser-driven photo-cathode using low-work-function materials such as Ba and lanthanum hexaboride (LaB_6) for improving the highly charged ion density of an electron beam ion source. This work is performed as a collaborative effort with the EBIS Group at Lawrence Livermore National Laboratory.

Ion Sources for Industrial Applications

Of the numerous private-sector collaborations we have had over the years, two of the most recent and significant involve ion beam projection lithography for integrated circuits, and ion implantation into substrates to make semiconductors on a large scale (e.g., for flat-panel displays).

Ion Beam Projection Lithography

In the past two years, the Plasma and Ion Beam Technology Group has been working closely with the Advanced Lithography Group (ALG) under a Department of Energy cooperative research and development agreement (Crada).

ALG has designed an ion projection lithography machine (ALG-1000) with the goal of projecting sub-0.18 μm patterns in a stencil mask onto a wafer substrate. The ion source requirements for the ALG-1000 machine are as follows: ion species are H+, H2+, H3+, He+; total useful current is greater than 20 μA; current density is greater than 50 mA/cm2; ion energy is between 10 to 15 keV; axial ion energy spread is less than 3 eV; and operation time between service intervals is greater than 500 hours. With equipment and personnel support provided by the ALG, we have been developing ion sources for use in ion projection lithography (IPL).

The low axial energy spread requirement is to keep the chromatic aberrations below 25 nm. The axial energy spread of accelerated ion beams has been measured with a retarding field electrostatic energy analyzer provided by the ALG. After two years of research and development, it has been demonstrated that the filter-equipped multicusp ion source is capable of producing ion beams with low axial energy spread (as low as 1 eV). The energy spread results have been found to satisfy the requirement of the application.

A filament-driven multicusp ion source for the ALG-1000 machine has been designed and fabricated. It was delivered to the ALG in May 1996 for integrated test of the IPL system. At present, we are operating the multicusp source with a 13.5 MHz RF-induction discharge. If the energy spread in this source scheme is low, the lifetime requirement for the ALG-1000 machine can be met.

The next generation IPL machines require ion energy spread below 1 eV. To meet this challenge, we are now developing a coaxial-type multicusp ion source. If the operation is successful, this new ion source configuration should be able to provide ion beams with axial energy spread below 1 eV. Achieving low axial ion energy spread is a goal not only for lithography but also for the nuclear physics program. Ion energy spread studies are definitely benefiting this program which requires low axial energy spread ions for production of radioactive ion beams. An ion source with axial energy spread less than 1 eV is needed to perform isobaric separation with a magnetic deflection spectrometer.

Sources for ion implantation

Use of multicusp ion source technology for ion implantation applications was studied under a CRADA agreement with Eaton Corporation. Next generation ion implanters will require special ion source performance to meet the fabrication requirements of semiconductor devices. The dissociation of gaseous compounds such as BF_3 or PH_3 into elemental boron and phosphorus ions is one of the research topics undertaken by the Plasma and Ion Source Technology Group. In addition, we are assisting Eaton Corporation in the development of ion sources for large area flat panel display manufacturing. Conventional implanters employ mass analyzing magnets to separate the desired ions from the extracted beam. Large area glass substrates are being used in

the fabrication of active matrix liquid crystal displays (AMLCD). Therefore, mass analysis is not practical. A technique has been developed at LBNL to selectively ionize the desired gas element. This approach will eliminate the excessive heating and over-charging on the glass substrate created by the unwanted species in the accelerated beam.

Plasma Technology for Accelerator and Fusion Applications

Aside from ion sources meant for accelerator injection, applications of our technologies can be very useful to the energy-research community. Here are two examples.

Titanium nitride coating of accelerator beam pipes

One of the problems encountered in many high-power RF systems is multipactoring inside vacuum cavities. The potential for multipactoring occurs whenever the secondary electron emission coefficient of the surface exceeds unity. The secondary electron emission coefficient of TiN is always less than unity. Therefore, a TiN coating can reduce multipactoring and also reduce photoemission electron from beam-pipe surfaces. A new technique has been developed at LBNL that will allow an efficient way to coat long pipes with differently shaped surfaces. In this technique, RF-induction discharge with an exposed Ti induction antenna coil is used. Preliminary results have shown that the method yields a uniform coating with a rate of 600 nm/hr. Further careful study will be necessary in order to enhance the quality of the coating. This method is of interest to many accelerator projects such as the B-Factory, the LANSCE upgrade, and the National Spallation Neutron Source.

Microbeam pulses for induction linacs

In order to minimize the required volt-seconds, induction linacs are operated with short beam pulses of about 20 μs in width and rise time less than 1 μs. Switching on ion beams by pulsing the discharge is too slow due to plasma formation time. An alternative approach is to keep the discharge and the extraction voltage at steady-state while the plasma flow into the extraction aperture is controlled by a combination of magnetic and electric fields. Short beam pulses with high repetition rate can be generated with a combined arrangement of fast electronic switches and a dc bias power supply.

The dc power supply and the electronic switch are installed between the plasma electrode and the source chamber wall. In normal operation, the plasma electrode is connected to the anode walls. If a positive voltage (~100 V) is suddenly applied to the plasma electrode, the plasma in front of the exit aperture is pushed away by the electrostatic field and the positive ion current disappear. The time response of the beam intensity follows closely the applied voltage. We are now collaborating with the Fusion Energy Research Program (see Chapter 1) to develop an appropriate source configuration and voltage modulator for use in the heavy ion fusion induction linac system.

Reported by Ka-Ngo Leung

Plasma Applications Group

The Plasma Applications Group explores and develops novel plasma- and ion-beam-based methods for materials synthesis and modification, as well as applications of novel materials created using these methods. The work is highly diverse, with applications to a very wide realm of science and technology.

Much of our work (especially the materials work) is collaborative with researchers elsewhere who have specific materials needs that are otherwise difficult or impossible to obtain. Over just the past year we have carried out (and generally published) work related to new materials in areas including:

- Super-hard surfaces
- High-temperature-tolerant coatings (Figure 6-3)
- Corrosion-resistant surfaces
- Improved lithium-battery electrodes
- Bacterial-infection-resistant surfaces
- Surfaces that engender good neuron growth
- Metal-ceramic bonding for novel dental restorations
- Fluorescence in rare-earth-doped materials including diamond
- Electromagnetic rail guns

We have also made many contributions relevant to high energy and nuclear physics research. These are emphasized in the remainder of this section.

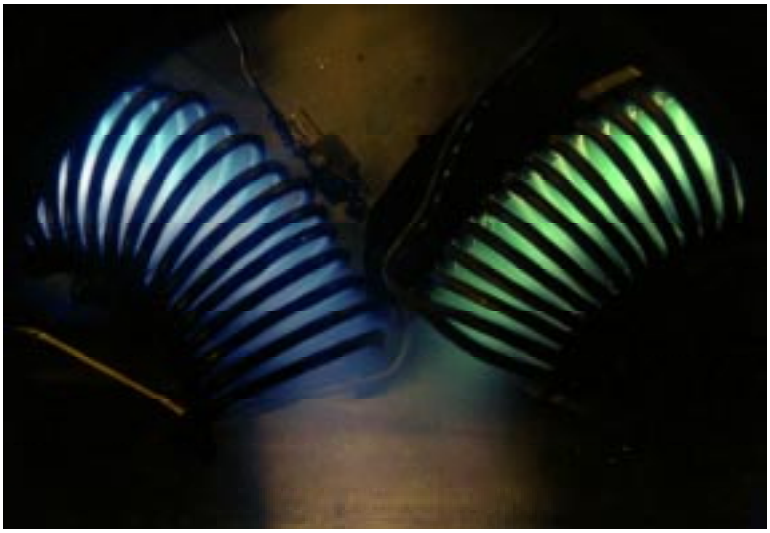

Figure 6-3. *In our "Dual-Source MePIIID" technology—usable, for instance, to deposit highly adherent, temperature-resistant coatings of Mullite ($3Al_2O_3.2SiO_2$) onto ceramics — metal plasmas from two separate plasma guns are brought together through independent magnetic channels and energetically deposited as a thin film on the chosen substrate. MePIIID means metal plasma immersion ion implantation and deposition.*

Resistivity Tailoring of Ceramic Accelerator Columns

There has been a need for many years for a means of tailoring the surface resistivity of ceramic accelerator injector columns. By making the resistivity uniform (though very high) rather than as high as possible (but inconsistent), this approach results in a uniform gradient of the surface electric field uniformly, thereby reliably obtaining the maximum possible voltage hold-off across the column. Collaborating with workers at the Jefferson National Accelerator Facility (formerly CEBAF), we've developed such a method.

Using our high-current metal-ion implantation facility fitted with a special fixture to hold and rotate the column, we've implanted the inside surface of the column with 130-keV Pt ions to a dose of about 3×10^{16} cm^{-2} so as to produce a uniform surface resistivity and a column resistance (load seen by the injector power supply) of close to 10 gigohms. We are able to accurately fine-tune the column resistance, an implication of which is that we can make matched pairs or sets of columns with equal voltage splitting. To date we have processed 4 CEBAF columns in this way - one test version, 2 matched columns for actual use, and a spare; several more are on the way. It is probable that this work will find more extensive application. See Figure 6-4.

Plasma Synthesis of Black Copper Oxide Coatings On B Factory Kickers

The transverse and longitudinal kicker structures for the PEP-II B factory at SLAC (see Chapter 4) have a unique cooling requirement in that they are heated by microwave power dissipation but good conductive heat sinking cannot be done. Radiant cooling can be adequate if a high emissivity black coating can be applied to the outside surface of the kicker and the inside surface of its surrounding structure. The coating must also be highly adherent, dense (void-free), and fully compatible with the ultrahigh vacuum of the B-factory vessel. We have used our energetic-ion plasma methods to form a black copper oxide film that serves this purpose well.

We did a virtually identical job for the ALS several years ago, and the performance of the black coating and the radiant cooling has been good. Based on this track record, we've recently been in "production mode" to similarly process a large number of kicker components for the B-factory. Several dozen pieces have been processed, some of them up to a meter long and 5 inches in diameter.

Plasma Synthesis of High-Electron-Emission Oxide Cathodes

The cathodes of electron guns in high power klystrons need to reliably produce high current density electron beams over long lifetimes. It is known that oxide cathodes (mixtures of Ba/Sr oxides on Ni) can produce very intense electron emission (up to ~100 A/cm^2) at relatively moderate temperatures (~900° C), but the reliability of this kind of cathodes has been unsatisfactory and so it has been virtually been abandoned, worldwide, in favor of the more reliable but high-temperature sintered tungsten cathodes. There is much to be gained by the development of a process for the reliable production of high-performance oxide cathodes.

In collaboration with the Klystron and Microwave Group at SLAC we have started exploring the feasibility of plasma synthesis of Ba/Sr oxide cathodes using our “MePIIID” (metal plasma ion implantation and deposition) technique. To date we have formed dense

(void-free) BaO films on test substrates and on a test electron gun cathode, and formed an electron beam of up to 1 A at 2 kV and 800˚ C (significant current for these preliminary voltage-limited tests, and at low temperature as well). This approach would be a boon for the Next Linear Collider, which as envisioned by SLAC would call for about 10,000 klystrons. Present-technology cathodes would cost several thousand dollars each, for a total of several tens of millions of dollars. Our plasma approach would produce dense, adherent, reliable, high-emission, oxide cathodes at a significant cost advantage. The technology would clearly be important for a wide range of industrial and commercial applications also.

Metallization of Ceramic Microwave Windows and Other Components

In another collaboration with the SLAC Klystron Group we are investigating the formation of highly adherent metal films (gold and other) on ceramic high-power microwave components, using energetic metal plasma deposition. Making good ceramic-to-metal bonds for a number of different applications in the microwave arena has been a thorn in this field. We have developed a plasma method of forming highly adherent metal films on diamond and ceramic substrates. Berkeley Lab has submitted a patent application for this process, and at least one manufacturer of CVD diamond products has expressed interest in licensing the technology.

In the collaborative program with SLAC we are concentrating on ceramic substrates (as used for microwave windows and other microwave components). Note also that the ability to tailor the surface resistivity of ceramics to high values (as described in the section on the CEBAF collaboration, above) could perhaps play a role in this application. The program is in the early stages but, based on our prior work, we are confident of success.

Surface Modification of Metals for High-Field RFQs

A limitation to the performance of RFQ accelerators is given by rf electric breakdown at the high-field parts of the accelerating vanes. The ability to increase the rf field level at which breakdown occurs would allow the RFQ to operate at higher MeV/m levels. With Berkeley Lab's participation in the Spallation Neutron Source project and the need to develop a very-high-performance RFQ for this purpose, the need to increase the rf electric field breakdown limit is critical.

In collaboration with the IBT RFQ Group we have initiated a program to develop metal surfaces with superior electric breakdown properties. Metallurgical hardness is thought to be a related required characteristic of the surface, and in this field we have much background experience (ion implantation for improved surface hardness). Furthermore, and as a nice example of the serendipity that occasionally follows from our highly diverse program, we have already addressed a very similar concern in another piece of collaborative work (with an Army laboratory) related to increasing the tribological (friction) performance and electric arcing resistance of electromagnetic railgun rails and armatures.

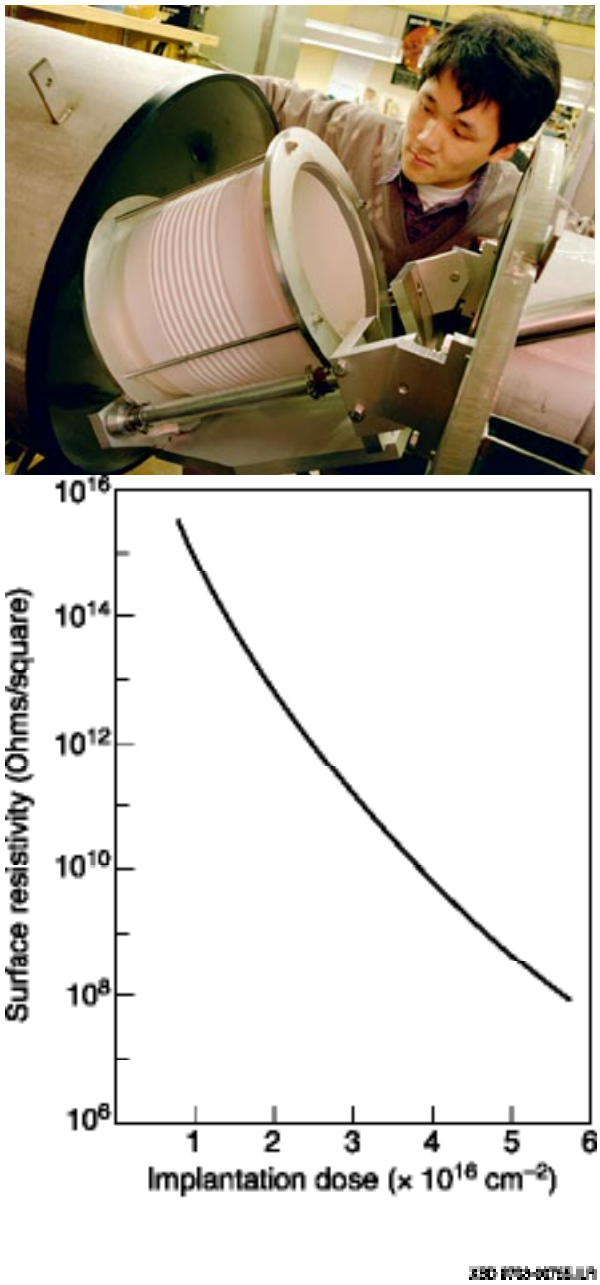

Figure 6-4*. Ceramic accelerator column for the Jefferson National Accelerator Facility (formerly CEBAF) FEL project about to be ion-implanted for surface resistivity tailoring. The process imparts a slightly lower (though still very high) and uniform resistivity to the column. This makes the surface electric field gradient more uniform than it would be if the resistivity were as high as possible but uneven, thereby maximizing the insulator's voltage-holding capability. The column is shown here as placed by Fenghua Liu, visiting scientist from Beijing Normal University, in its implantation cradle. The cradle positions it at the appropriate angle with respect to the broad ion beam while slowly rotating it in the beam. Also shown is a graph of resistivity vs. dose for the few-centimeter-square coupons we used in our initial exploration of the process. It is probable that this work will find applications well beyond the accelerator community—perhaps in electric power generation and distribution, for example.*

Aluminum Contact Resistance Enhancement for RFQ Development

The Ion Beam Technology Program's RFQ development uses aluminum structures (for reasons of machining and cost) for research and prototype RFQ testing. Because the levels of rf electric fields and current densities are so high, there is a concern about contact resistance at mating aluminum surfaces; the surfaces, having been exposed to air, are of course not aluminum but

rather aluminum oxide, and the contact resistance is unacceptably high. It turns out, again serendipitously as a result of work carried out some time ago for another purpose, that we have a method for lowering the contact resistance of aluminum electrical joints. The method has been developed and quantified.

In our approach, a thin film of gold is atomically mixed into the aluminum surface to remove the native oxide layer and prevent further oxidation. The contact resistance has in this way been lowered by three orders of magnitude. We will utilize this energetic metal plasma technique to process critical aluminum RFQ joints.

Possibilities for a Mevva Ion Source for Inertial Fusion Energy

AFRD's approach to fusion energy, involving beams of heavy ions (see Chapter 1), calls for an ion source with some unique characteristics. It should produce a high current (about 1 A), broad beam (10-15 cm diameter) of short pulse duration (2-20 ms), containing heavy ions (A = 100 - 200), preferably multiply stripped (Q = 2+ or 3+), in a low-divergence and quiescent beam. Following the initial development of the vacuum arc ion source (a 2-time R&D-100 winner) by our group some 10 years ago, a small amount of exploratory work was carried out to determine the suitability of this kind of ion source for heavy ion fusion; the results were deemed negative and this avenue was not pursued.

In the decade since then, the performance of this kind of source has been improved vastly in many different ways. (Interestingly, a lot of the credit for the development of metal vapor vacuum arc ion sources ("Mevvas") for accelerator injection goes to German (GSI) and Russian (Tomsk and ITEP) workers; a Mevva source is now used routinely for high current heavy metal ion injection into the GSI UNILAC and SIS facilities).It is thus appropriate to re-assess the suitability of this approach to HIF injection. In collaboration with a small company, we have completed a DOE/Small Business Innovation Research Phase 1 evaluation of the approach. The experimental results were very good, and all of the Phase 1 objectives were met. A Phase 2 proposal has been submitted and we anticipate support. An end product of this program would be a novel, flexible, high-performance ion source for the fusion program.

Accelerator-Based BNCT Clinical Trial

The Department of Energy's Office of Health and Environmental Research has been supporting a boron neutron capture therapy (BNCT) clinical trial conducted at the Brookhaven Medical Research Reactor. Encouraged by the Phase I results over the past 2 years, BNL researchers are continuing clinical trials at a higher dose of radiation under another protocol (Phase II). Another clinical study with a limited scope is underway at the Massachusetts Institute of Technology research reactor. Reactor facilities in Petten, the Netherlands, and in Helsinki, Finland have been

readied for BNCT clinical trials. In Japan, a clinical trial is expected to continue at the newly renovated Kyoto University Reactor facility.

Realizing that all the facilities used or planned for BNCT clinical trials are based on existing nuclear reactors, and furthermore that future hospital-based BNCT facilities must be accelerator-based as no reactors will be allowed in medical centers in metropolitan areas, we have started a program to build an accelerator-based BNCT facility at LBNL as the basis of an LBNL/UCSF initiative to conduct integrated scientific and clinical research in BNCT. The research is jointly conducted by a group of investigators assembled from LBNL, UC Berkeley and major university medical centers on the West Coast.

In December 1995 we submitted a field task proposal to DOE/OHER for the development of an accelerator-based BNCT facility at LBNL, including an electrostatic quadrupole (ESQ) accelerator, a neutron-production target, a neutron beam shaping assembly, a treatment room, and a treatment control system. In August 1996 DOE/OHER conducted a peer review of the FTP. Although the objectives of the FTP are limited to preparation of an accelerator-based BNCT facility at LBNL, the committee reviewed the entire LBNL/UCSF BNCT initiative, the major agenda item being whether another BNCT clinical trial should be supported on the West Coast.

The topics covered in the review included:

- Drug development
- Drug localization biology (cell studies, small animal studies, large animal studies)
- Biodistribution pharmacokinetics
- Treatment planning and dosimetry
- Concept for a Phase I study
- Proposed BNCT clinical trials
- 2.5-MeV electrostatic-quadrupole dc accelerator (mechanical system, electrical system, ion source, and proton transport line)
- Neutronics and target design, and
- BNCT facility layout.

The results were very favorable, as indicated by this statement:

> The reviewers were unanimous (an unusual event) in rating the overall program as excellent. LBNL was judged to have the requisite technical expertise and experience to successfully construct and operate the accelerator neutron source. Support facilities and personnel at LBNL are excellent. Although there is no guarantee that the proposed accelerator will deliver a sufficient neutron flux for successful BNCT, it is highly probable that fundamental advances will be made and that the project will have a major impact on clinical applications. The marriage of clinical/preclinical researchers at UCSF with the skilled accelerator team at LBNL is a major strength of the proposal. The investigators on the clinical side are a well qualified group with representatives from all necessary aspects including drug development, drug testing, pharmacology, medical imaging, patient treatment and clinical trial design. The support of the Brain Tumor Research Center at UCSF is very important, and the collaboration of the other institutions in the West Coast NCT Association will make it possible to execute large scale clinical trials...

For the FTP we have received $300k in FY1996, and following the review an additional $300k in FY1997. Within the confines of the limited funding we have started research and development projects, focused on the development of a high-current ESQ power supply, a high-power neutron production target, and a moderator assembly for optimization of epithermal neutron beams. We are proceeding on the assumption that the funding situation will improve so that this aggressive, highly focused project will proceed into clinical trials on human subjects at this LBNL facility by the end of the decade. The clinical trials will be supported by strong pharmacological and biological studies of effective tumor-seeking boron compounds, *in situ* biodistribution kinetic measurements of boron compounds, neutron dosimetry, and clinical physics. LBNL has supported the biology and biodistribution studies of boron compounds through Laboratory-Directed Research And Development Funding ($129k in FY1996 and $175k in FY1997), and the LBNL/UCSF scientists plan to seek research funding for scientific and clinical research outside of DOE/OHER.

Reported by William T. Chu, LBNL, and Ted Phillips, University of California, San Francisco

Technical Progress, April 1996 – March 1997

The basic reaction we have chosen for neutron production is ^{7}Le(p,n)^{7}Be. Our analysis has shown that an accelerator capable of delivering a 2.3–2.5 MeV proton beam with a 20 mA DC proton current, coupled with an optimized neutron moderator assembly, would produce epithermal neutron beams that can not only match the Brookhaven Medical Research Reactor in dose rate and treatment time but also offer significant advantages in terms of neutron beam quality and clinical efficacy. Figure 6-5 illustrates the overall scheme, and Figure 6-6 compares the various neutron sources available.

Accelerator design study

The design is based on the goal of reusing parts of the "Adam" injector salvaged from the SuperHILAC and converting it with an ESQ accelerator. Besides the accelerator column, we decided to replace the original shunt-fed Cockcroft-Walton power supply (capable of delivering up to ~7 mA) with a more powerful power supply (20 mA and upgradable to >50 mA).

The accelerator assembly is enclosed inside a 6.1 m long 2.4 m diameter steel tank at 125 psi pressure. At the front end is a multicusp H^+ ion source that can deliver ion beams with better than 80% pure atomic fraction (the remaining fraction is comprised of H_2^+ and H_3^+ molecular ions) By installing a molybdenum liner around the inner chamber surface, it is found that the rf driven multicusp source can deliver a beam with proton percentage as high as 94%.[1] Adjacent to the ion source is a 325 kV low energy beam transport section (LEBT) which consists of 6 electrodes. The main acceleration is done by 13 ESQ modules. One extra non-accelerating ESQ is placed at the end for beam matching into the transport line. The ESQ has a bore diameter of 6 cm. The column is 3.8 meter long and is made of 70 alumina rings that are 45 cm in diameter. The design is modular; each ESQ module has several alumina rings brazed together and the full assembly is held under compression by tie rods. Typical potential difference across the ESQ electrodes is 120 kV. The machine is designed to limit the electric field stress (calculated by the 3D code) to less than 45 kV/cm for vacuum gaps and less than 8 kV/cm for insulator surfaces.

[1] K.-N. Leung, "Ion sources for high purity ions," presented at the Fourteenth Int. Conf. on the Application of Accelerators in Research and Industry, Denton, Texas, November 6-9, 1996; to be published in Nucl. Instrum. and Methods in Phys. Res., 1997.

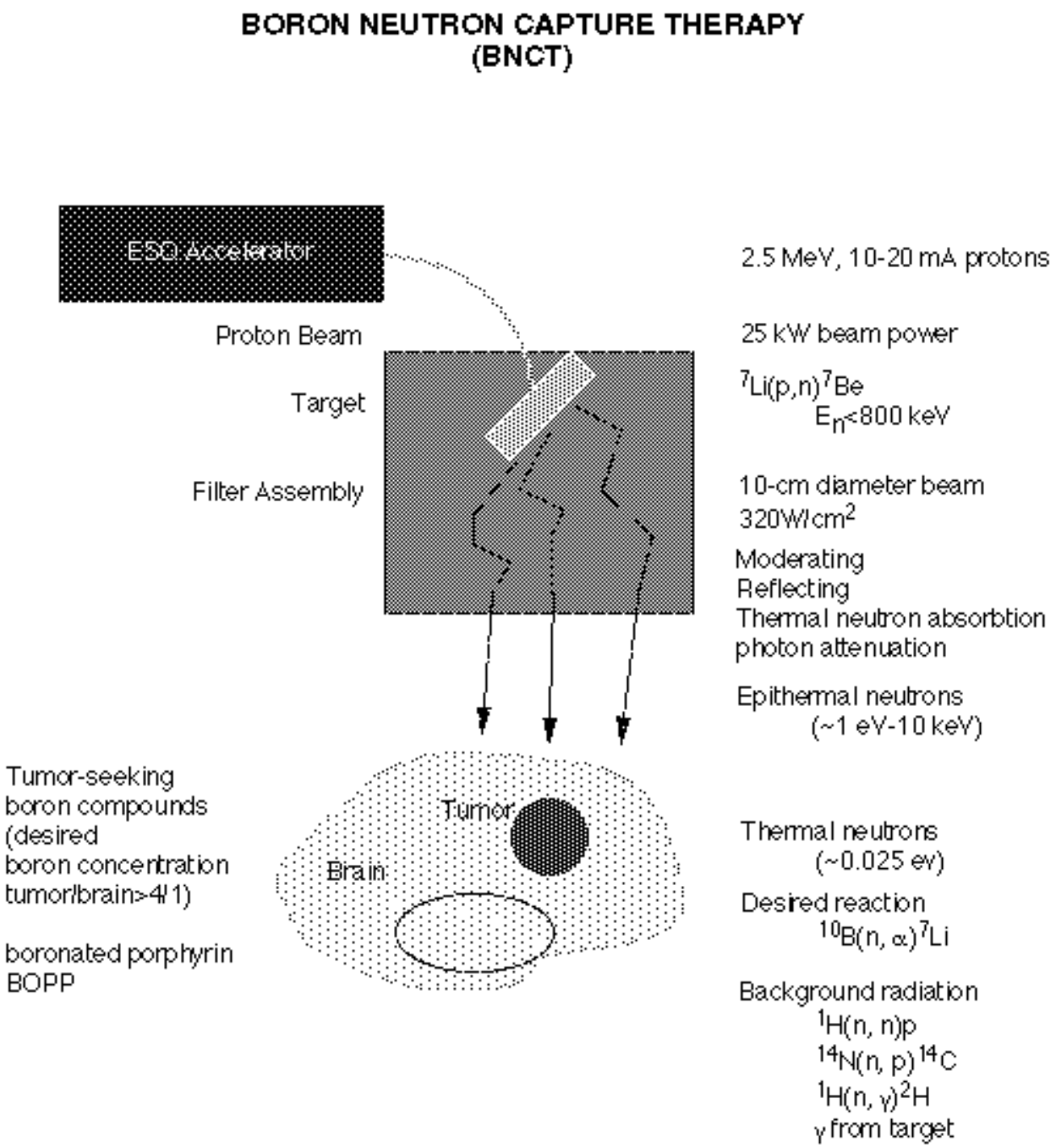

Figure 6-5. *Conceptual diagram shows how BNCT works.*

A computer simulation using the WARP-3D particle code shows that the average size of the beam envelope for a 25 mA proton beam is only 3 mm radius which is about 10% of the bore radius. The machine can accelerate a 125 mA beam with a beam envelope about twice the size at 25 mA, but still only 20% of the bore radius. The ESQ accelerator is capable of providing a

wide range of beam current to meet the treatment requirements. By varying the beam current to match the accelerator voltage according to a simple scaling law, the final beam energy is variable up to a maximum of 2.5 MeV. [2]

Once the proton beam is accelerated to full energy, it will be transported to the target area through a beam line consisting of a magnetic focusing lens (which is also useful in separating the heavier molecular ions from the protons to prevent wasting heating of the target surface) and a wobbler to spread out the beam spot size.

Reported by Lou Reginato

ESQ Power Supply Design Study

The Adam Injector power supply was modified to test the coupled transformer technology for generating 2.5 MV at currents up to 100 mA. Initial low level tests were performed on the impedance and voltage distribution along the high voltage structure. The tests indicate that the coupled transformer technology offers an order of magnitude lower impedance than the shunt-fed capacitively coupled Dynamitron type of drive, which means that 100 mA should be achievable.[3] The voltage induced in the secondary coils has been equalized to about 20% by adjusting the current density in the primary coil. Some work remains to bring the voltage variation down to about 10%. The final fine tuning will be done by adjusting the number of turns in the secondary coils. In the remainder of FY1997, we will also wind a full voltage secondary coil and use it to accurately map the induced voltage along the length of the injector and we will complete the final design of the oscillator, primary coil, secondary coils, rectifier, filter and protection system.

A preliminary cost estimate of the modifications to the Adam Injector power supply indicates that because of the existence of the major components such as the DC power supply, the high power modulator, and the pressure vessel with the high voltage dome and supports, the entire injector will cost about 50% as much as the Radiation Dynamics, Inc. (RDI) Dynamitron. The upgrade to the Adam injector power supply should produce a more robust power source with greater current capability and easily adaptability to the ESQ accelerator system.

Reported by Lou Reginato

Neutron-Production Target

A beam of 2.5 MeV protons at a beam current of 20 mA presents a heat-load of 50 kW to the target. For a proton beam with a Gaussian beam profile impinging on a target area of 100 cm^2, a peak heat-load of 1280 W/cm^2 would result (the worst case estimate). The heat-load per unit area can be cut in half by tilting the target to a 30° angle in respect to the proton beam.

An engineering analysis indicates that a water-cooled lithium metal target is feasible. The design is based on a convectively cooled aluminum substrate coated by a 45 μm thick Li layer (the effective thickness is 90 μm). Employed is the microchannel absorber concept in which heat is dissipated by water flowing through closely spaced, narrow coolant passages cut into the back side of the heat absorbing surface. Optimizing the channel geometry for a substrate

[2] J Kwan, "Designs of an ESQ Accelerator for BNCT Applications," *ibid.*
[3] L. Reginato, "Designing power supplies for 2.5-MeV 100-mA cw or dc applications," *ibid.*

fabricated from aluminum, the thermal response was calculated using the finite-element code ANSYS. A flow velocity of 9 m/s and a water temperature of 20°C were chosen as cooling parameters. The thermal analysis resulted in that the maximum temperature on the heat absorbing surface does not exceed 140°C which is well below the melting point of lithium. The maximum thermally induced stress encountered in the cooling substrate is about 130 MPa, which is less than the yield strength of pure aluminum.

A prototype aluminum target panel has been fabricated. Using wire EDM, both the heated surface and back plate could be machined from a single plate in one operation. The panel will be heat-load tested at the Plasma Materials Test Facility at Sandia National Laboratory in Albuquerque, NM. At this facility a defined heat-load profile can be delivered to the target utilizing a scanned electron beam. The thermal response curve up the operating heat-load will be determined, the thermal fatigue reliability of the prototype for up to 50,000 cycles will be demonstrated, and the thermal response curve up to twice the operating heat-load determined.

Reported by Bernhard Ludewigt and Russ Wells

Neutronics Studies

Moderator assemblies for proton beam energies between 2.1 and 2.5 MeV were studied in order to evaluate the clinical efficacy of accelerator-produced epithermal neutron beams. Our aim was to establish accelerator and target design parameters starting from clinical requirements. The study included the investigation of different moderator and reflector materials and geometries and the determination of the optimal proton beam energy.

The ^{7}Li(p,n) reaction has a threshold of 1.88 MeV and a strong resonance at 2.3 MeV with a resonance endpoint at about 2.5 MeV. Most studies to date have assumed that the optimum proton beam energy is 2.5 MeV for producing the highest epithermal neutron flux. We have performed detailed analyses of this reaction to investigate the tradeoffs between increasing target neutron yield and increased moderation losses as the proton energy is increased from 2.1 to 2.5 MeV. The result is that the epithermal neutron flux, defined as flux of neutrons with 1 eV $< E_n <$ 10 keV at the moderator exit, is roughly constant for proton energies from 2.3 MeV to 2.5 MeV for the moderators investigated.[4]

The moderator assembly was simulated using the Monte Carlo radiation transport code MCNP. The evaluation of the epithermal neutron beams and the estimation of the treatment times were based on calculation of depth-dose distribution inside the patient body. For this purpose, we have modified the INEL treatment planning program RTT, which is currently the basis for patient treatment planning at BNL, to accept the MCNP neutron current output. A mixture of 60 % Al and 40 % AlF_3, was shown to be superior to D_2O or BeO moderators. With the Al/AlF_3 moderator and a 20 mA proton beam the BMRR treatment time of 40 min can be matched. In addition, the tumor depth dose distribution is clearly superior for the accelerator produced beam. For example, for a single beam the dose at 8 cm depth is 21 Gy-equivalent in the accelerator case compared to 14.5 Gy-equivalent for the BMRR beam.[5]

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[4] DL Bleuel and R.J. Donahue, "Optimization of the ^{7}Li(p,n) Proton Beam Energy for BNCT Applications," LBNL Report LBL-37983 Rev. 1, May 1996.

[5] DL Bleuel, R.J. Donahue, and BA Ludewigt, "On Optimizing the ^{7}Li(p,n) Proton Beam Energy and Moderator Material for BNCT," presented at the Fourteenth Int. Conf. on the Application of Accelerators in Research and

The difference in the depth-dose distribution means that the tumor dose at depth can be significantly increased, possibly resulting in different clinical outcomes. The difference between the accelerator-produced spectrum and the reactor spectrum is largely due to much lower average neutron energy entering the moderator for the accelerator-produced neutrons, requiring less moderation and producing a much reduced broadening of the neutron energy distribution. Our analysis has shown that accelerator-based epithermal neutron sources can not only match the BMRR in dose rate and treatment time but also offer significant advantages in terms of neutron beam quality and clinical efficacy.

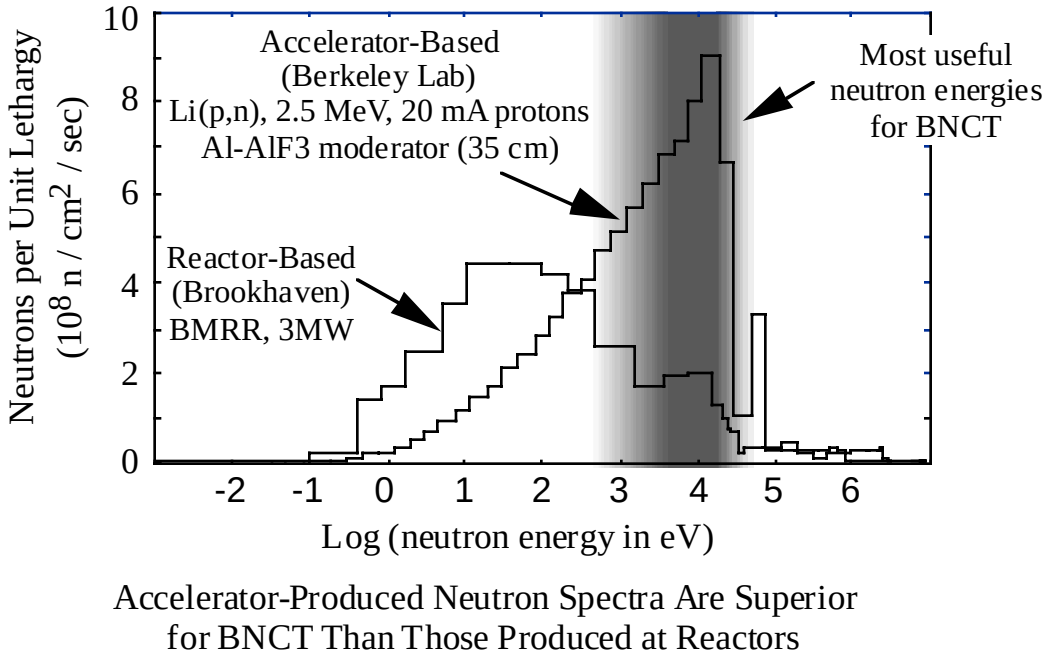

Figure 6-6. *Comparison of the effectiveness of various neutron sources for BNCT.*

In a separate study we investigated radiation shielding requirements for the treatment room and patient organ doses.[6] The radiation doses to the major organs of a patient received during a treatment were determined by simulating the radiation transport with MCNP using the MIRD 5 anthropomorphic phantom. Doses were tabulated by component for a given uniform ^{10}B loading in all organs. Such an analysis is needed to estimate the effect of the drug dependent boron loading of specific organs and the impact of patient positioning and shielding.

Reported by Bernhard Ludewigt

Industry, Denton, Texas, November 6-9, 1996; to be published in Nucl. Instrum. and Methods in Phys. Res., 1997; also LBNL Report LBL-39057, September 1996.

[6] S.V. Costes, R.J. Donahue, J. Vujic, "Radiation Shielding and Patient Organ Dose Study for an Accelerator-Based BNCT Facility at LBNL," LBNL Report LBL-39450, October 1996.

Facility Design

We have evaluated a number of siting options for the accelerator-based BNCT facility, and adopted a preferred location at Bldg. 51B (now-closed Bevalac external beam area) that takes maximum advantage of existing supporting infrastructure. The new BNCT treatment room will be developed in an existing shielded area (Cave 3) formerly used as a treatment room by the heavy ion biomedical program. We have started the seismic studies of the shielding structure of Cave 3 prior to making necessary modifications. It is located in close proximity to the Laboratory's nuclear medicine facilities, the imaging facilities and the isotope production cyclotron. Logistics of relocating the Adam injector from its present location to the proposed site have been worked out.

Biology of BNCT

LBNL has been supporting BNCT biology research through LDRD ($129,000 in FY96, and $175,000 in FY97). The biological research was concentrated on *in vitro* and *in vivo* cytotoxicities and pharmacokinetics of boron compounds, especially of boronated porphyrin or BOPP.[7],[8],[9],[10],[11],[12] We are also developing the protocols by which the uptake, clearance, and metabolic fate of proposed BNCT compounds can be monitored *in vivo* in both animal models and human patients. We have started investigating radiolabeling of the compounds with positron-emitting isotopes (^{18}F, ^{64}Cu, ^{11}C) and using our Positron Emission Tomography (PET) facility to follow the biodistribution of these compounds via radioimaging. The work was conducted at LBNL, UCSF, and UC Berkeley laboratories.

Plans

Our concentrated efforts will continue to be in the research and development of a completely equipped and tested ESQ-based BNCT treatment facility at LBNL ready to conduct clinical trials by the end of the decade. Specifically, we plan to convert the Adam injector to an ESQ accelerator with a new ion source, design and fabricate a neutron-production target, a neutron

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[7] S.M.J. Afzal, E.A. Blakely, D. Callahan, W. Chu, S. Kahl, J. Tibbitts, A. Bollen, L. Hu, J. Fike, W. Bauer, T.C. Phillips, and D.F. Deen, "BOPP: A New BNCT Compound," presented in a Workshop at the 44th Annual Meeting of the Radiation Research Society, 14-17 April 1996, Chicago, IL.

[8] E.A. Blakely, S.M.J. Afzal, D. Callahan, W. Chu, S. Kahl, J. Tibbitts, A. Bollen, L. Hu, J. Fike, T.C. Phillips, and D.F. Deen, "BOPP: Cytotoxicity, Pharmacokinetics and Intracellular Localization in a Human Glioma Cell Line and Biodistribution in a Canine Model," presented at the PTCOG XXIV and International Particle Therapy Meeting, “Current status and future directions in particle therapy," 24-26 April 1996, Detroit, MI.

[9] D. Deen, J. Afzal, E. Blakely, A. Bollen, D. Callahan, W. Chu, L. Hu, S. Kahl and T.L. Phillips, "BOPP: Cytotoxicity, pharmacokinetics and intracellular localization in a human glioma cell line," presented at the Seventh International Symposium on Neutron Capture Therapy For Cancer, 4-7 September 1996, Zurich, Switzerland.

[10] D. Callahan, T. Forte, J. Afzal, D. Deen, S. Kahl, K. Bjornstad, W. Bauer, T. Phillips, and E. Blakely, "Boronated Protoporphyrin (BOPP) Localizes in Lysosomes of the Human Glioma Cell Line SF-767 With Uptake Modulated by Lipoprotein Levels" (manuscripts in preparation).

[11] J. Afzal, E. Blakely, L. Hu, J. Fike, S. Kahl, K. Bjornstad, T. Phillips, and D. Deen, "BOPP: Cytotoxicity and Pharmacokinetics in a Human Glioma Cell Model" (manuscripts in preparation).

[12] T. Ozawa, J. Afzal, J. Wang, A. Bollen, J. Wyrick, J. Fike, E. Blakely, G. Ross, T. Phillips, and D. Deen, "BOPP: Cytotoxicity and Biodistribution in Rodent Tumor Models" (manuscripts in preparation).

15. J Tibbitts, J Fike, A Bollen, W Bauer, T Seilhan, T Phillips and S Kahl, "Pharmacokinetics and Toxicology of BOPP in the Normal Canine" (manuscripts in preparation).

beam shaping assembly (filters and moderators), and prepare a treatment room and ancillary facilities including neutron dosimetry equipment and patient irradiation control system.

Dual Axis Radiographic Hydrodynamic Testing (DARHT)

The DARHT project is a two-accelerator flash X-ray facility, to be constructed at Los Alamos National Laboratory, which will perform radiographic simulation studies of nuclear weapon hydrodynamics. It is the successor to the PHERMEX facility, which is 30 years old. Originally DARHT was planned to generate two single x-ray pulses incident on the experiment from two perpendicular directions and coincident in time to create a 3D image. The weapons community users have since stated that a configuration generating multiple shots to achieve time resolution is more desirable. Therefore rather than simply duplicate the first-axis machine in the second axis, a Technology Options Study (TOS) is being conducted to chose a technology for the second axis that will provide four sequential pulses of 50-80 ns in width separated by nominally 500 ns. The TOS involves three options:

1. A four-short-pulse induction linac using cores similar to the DARHT first axis machine, but with a series-parallel set of 4 pulse lines to drive the cores and with complete reset occurring between the pulses.
2. A long-pulse induction linac that generates a single 2-μs-flattop electron pulse, together with a magnetic beam chopper that creates the four short pulses.
3. An inductive voltage adder diode system.

LBNL's prime responsibility is in option 2, with a support role in option 1. Option 3 is the responsibility of Sandia National Laboratory.

The DARHT Program at Berkeley Lab

Our DARHT team consists of people from AFRD's Heavy Ion Fusion and Ion Beam Technology Programs, the Engineering Division, and Lawrence Livermore National Laboratory. The first-axis machine is expected to provide a single 60 ns electron pulse at 19.75 MeV focused to a spot on the x-ray conversion target of 1.2 mm. The expected dose at 1 m is to exceed 1000 R. The second-axis machine must have very high probability of reaching at least this level of performance. In addition, the second-axis machine is required to have a high probability of producing four pulses in the nominal 2 μs window separated by 250-500 ns. The expected spot size on target is 1 mm or less, and the expected x-ray dose is to be near, but less than, 2000 R at 1 m. There are a number of operational requirements imposed by maintenance turnaround time that primarily dictate shot-to-shot repeatability, focal spot motion during the shot, and the number of shots required just to set up the x-ray imaging equipment.

The LBNL long pulse linac (Figure 6-7) is an outgrowth of the work on heavy ion fusion linacs. The injector is a 3 MV diode using an 8 inch diameter dispenser cathode. The beam emittance at the target must be less than 1200 π mm-mrad normalized, to get the 1 mm desired spot size. Therefore velvet cathodes, used in other machines of this type, are not suitable. The diode is powered by a crowbarred Marx generator which is mounted vertically in a pit. Two circuits are contemplated for the diode drive. One is the full 2 μs pulse with 300 ns rise and fall times. The other has a 100 ns flat region pulse also with 300 ns rise and fall time to allow both single pulse operation of the machine and commissioning with a lower energy pulse.

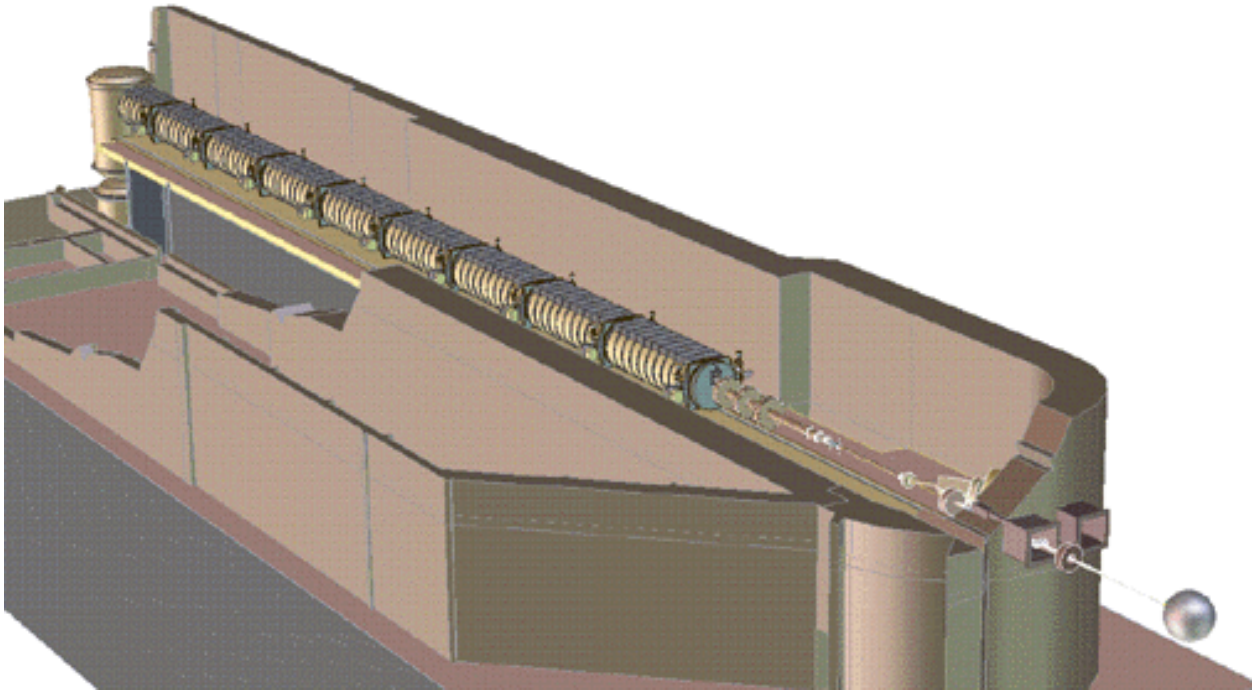

Figure 6-7*. The long-pulse option for DARHT. The accelerator hall is of order 60 m long.*

The accelerator itself consists of 87 induction cells at 194 kV per cell. The beam tube radius is 127 mm . Each cell weighs 4000 kg and is made of 2605 SC Metglas wound with Mylar insulation. The cores are 775 mm radius and 480 mm long. Each cell has a Rexolite insulator which separates the oil dielectric around the cores from the vacuum region. A full-scale mockup experiment was conducted to measure the transverse mode impedance of the

cavities and to verify the breakdown resistance of the insulators. The impedance of the TM_{120} mode was shown to be damped by proper positioning of ferrite dampers. Also, good agreement between the AMOS code and the experiments was achieved. Beam breakup does not appear to be a problem in this design.

Three diagnostic stations are planned at 8.3, 14.3, and 20 MeV with an additional total current measurement at the injector exit. The beam chopper uses a small fast magnetic kick that deflects the beam to one side or the other of a permanent magnet septum. This chopper system is being designed at Lawrence Livermore National Laboratory. The short pulses from the chopper pass into a final transport system that consists of a chicane that traps debris flying back from the target, then a final-focus system. This final transport system is the responsibility of Berkeley Lab and will be used on either the long-pulse or the short-pulse linac option. The final focus system is a pulsed 2 T solenoid with its center 125 mm from the focal spot. It will focus particles adequately within a $\pm$ 3% momentum range. Plasma that streams back from the target makes it necessary that the beam be steered to a new target at each pulse. The target array is three targets at the vertices of an equilateral triangle plus one in the center. The distance from center to the vertices is 5 mm. Pulsed ferrite-C magnets placed in front of the focusing solenoid steer the beam to these different targets.

In addition to designing the chopper, the Livermore group is also responsible for the beam envelope, corkscrew, and beam breakup calculations using input parameters from the Berkeley Lab injector designers. They are performing this task on the short pulse linac also. Total machine emittance calculations are the responsibility of Los Alamos National Laboratory for both concepts. Berkeley Lab's Engineering Division is providing engineering support for the short pulse concept and support for some experiments performed in AFRD as part of the short pulse study. These experiments involve core reset, core material magnetic properties, and power coupling. AFRD has supported multipulse insulator breakdown tests with voltage reversal for the short pulse study.

After the option for the second axis is chosen, Berkeley Lab will continue to be involved in the construction project if one of the linac options is chosen. The IVA-diode concept is purely a Sandia National Laboratories initiative.

Reported by Henry Rutkowski