FINAL REPORT

Channeling-Radiation Project for Department of Energy

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Office of Intellectual Property Counsel
DOE Field Office, Chicago

2/13/99
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Mr. Terry Vlasich
U.S. Department of Energy
9800 South Cass Avenue
Argonne, IL 60439

Subject: Final Report for Contract DE-FG02-90ER81034, SBIR Phase II

Dear Mr. Vlasich,

SFA Inc. encloses herewith the final report required by the subject contract. This report covers the work performed during the period of September 15, 1991 to February 15, 1998.

Please call me if you have any questions.

Sincerely,

A handwritten signature in cursive script, appearing to read 'Redge Mahaffey', with a long horizontal flourish extending to the right.

Redge Mahaffey, Ph.D.
Senior Vice President

SECURITY CLASSIFICATION:

UNCLASSIFIED

SFA - 98/001F

Channel-Radiation Project - SBIR PHASE II

Prepared by:

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Final Report**

Prepared for:

**Terry Vlasich
U.S. Department of Energy
9800 South Cass Avenue
Argonne, IL 60439**

Final Report of the SFA Channeling-Radiation Project to the DOE

1. Introduction

The objective of the project was to demonstrate the feasibility of producing and utilizing a channeling-radiation beam at a typical medical electron accelerator. The experiment was performed at the National Institute of Standards and Technology, using the 33-MeV electron LINAC known as the Medical/Industrial Radiation Facility (MIRF). The experiment consisted of two distinct stages, designing and assembling an extension to the existing beam line, and running the experiment using silicon and diamond crystals. The first part of the experiment was very time-consuming, owing to the necessity of building up the infrastructure of the facility as we developed and instrumented the beam line. This left little time for the actual feasibility tests, and in the end the experiment was terminated due to time pressures and funding availability. Therefore, the results presented here do not include channeling-radiation spectra from diamond.

For the first of these two stages, a brief but comprehensive account of our performance is given on the design and assembly of the beam line. In spite of our strenuous efforts to complete the second stage, only a very brief and incomplete report can be given at this time. We note that if funds can be found to finish the project, a major step has already been taken. Section 2 contains a description of the beam-line assembly and the beam-tuning procedures followed during the course of the experiment. Section 3 presents the results of the measurements to date.

2. The Beam Line and Experimental Equipment

2.1. Beam Requirements

A particle beam directed along the axis of the crystal cannot exceed a certain angle if it is to be channeled by the crystal. Therefore, it is crucial to maintain the beam within the limits of this angle, which is called the critical angle ψ , in order to achieve particle channeling. This angle is determined by the magnitude of the potential barrier U_B , which is limited by thermal vibrations,

$$\psi_{\text{axis}}^2 \cong U_B/E.$$

Generally, for medium to light elements $U_B \cong 100 \text{ eV}$, and for heavy elements it is about 1000 eV. Typically for $E \cong 1 \text{ MeV}$, the angle is close to one degree. The critical angle for planar channeling is estimated by

$$\psi_{\text{plane}}^2 \cong Y_{\text{max}}/E,$$

where Y_{max} is of the order of one-third to one-half of the axial potential, depending on the crystal and the plane chosen.

In order to achieve the minimum beam quality suitable for an electron-channeling experiment, the beam divergence of MIRF had to meet the essential requirement that it not exceed the critical angle. We therefore performed a series of preliminary tests at MIRF before assembling (or even designing) a beam line. These tests were done using chromatographic films placed at different locations along the proposed beam line, and the results were satisfactory, as far as the beam divergence was concerned. A simple calculation shows that the critical angle for a 25-MeV electron beam (our chosen energy) bombarding a diamond crystal is roughly equal to 2 milliradians. The preliminary tests showed that the beam divergence is well within this limit. Later, after assembling the extended beam line, a second method was utilized to check the beam divergence at the position of the crystal, detailed in Section 2.7 below.

2.2. Beam-Line Design

The beam line consists of the following components (ordered from upstream to downstream):

- Main slit (5-mm);
- Focusing quadrupoles (Q1-Q4);
- First collimator/viewing-screen assembly ($\delta 1$);
- Goniometer (isolated by two vacuum valves);
- Sweeping magnet (43-deg);
- Straight-ahead beam line:
 - Second collimator/viewing-screen assembly ($\delta 2$);
 - HP-Ge detector assembly;
- Beam-dump line:
 - Focusing magnets (Q5-Q6);
 - Beam dump (electrically isolated).

Figure 1 is a schematic drawing of the entire beam line. A detailed view of the central part of the beam line is shown in Fig. 2.

It would be preferable, of course, to have another bending magnet in the beam line, upstream from the goniometer, so that the detector does not view the main energy-analyzing slits directly. This alignment of the main slits and the detector assembly was the cause of considerable background in the detector. Our first results were promising enough to persuade us to continue, before any attempt was made to improve the beam line. The remedy is simple in principle, but would have been costly in time and equipment; thus, this background reduction was never realized.

2.3. The Beam Tubes

The diameter of the beam tubing had to be selected to avoid the background that would be caused by non-channeled electrons striking the walls of the beam tubes. In order to take multiple-scattering effects into account, the length of the straight-ahead beam line (about 8 m) dictated the choice of 2½"-diameter beam pipes, corresponding to a mean multiple-scattering angle of close to 2 mrad. This special beam line in turn required us to design and build special stanchions.

This choice of tubing diameter also required modifications in the Q5-Q6 focusing assembly. Since this assembly was provided by NIST, these modifications also were done at the shops at NIST.

Special windows made from Kapton were provided by the MIRF staff.

The entire beam-line assembly was aligned using a laser beam shot from the detector end of the beam line. The alignment was done by lining up the two collimators ($\delta 1$ and $\delta 2$) with the main slits. The alignment procedure was reiterated several times.

2.4. Beam Monitoring

A series of standard beam-monitoring devices were used in the control room to monitor parameters such as counting rates and beam currents (in the pA-to- μ A range). The entire monitoring ensemble was connected to the accelerator hall through a patch panel. At times this single patch panel proved to be insufficient, so that additional signal and isolated-power cables had to be installed.

A series of closed-circuit video cameras, provided by the MIF staff, was extremely handy for monitoring the beam size and shape (on the fluorescent viewing screens), the magnetic field in the sweeping magnet (read with a Hall-effect Gaussmeter), and the sweep-magnet power-supply current. We could navigate and zoom two out of the total of six cameras remotely, which was very valuable during experimental tests.

2.5. Control of Mechanical and Electrical Components

As mentioned in the list above, two collimator/viewing-screen multifunctional inserts were located at two critical positions in the beam line. These mechanical assemblies were driven electrically and controlled from a PC in the control room. The computer control was done in a LabView-CAMAC environment. A more detailed description of the computerized controls is given in Section 2.8 below. The collimator/viewing-screen assemblies are called $\delta 1$ and $\delta 2$. At any given time we were able to monitor the beam shape and the focusing by inserting one of the BeO viewing screens at either the $\delta 1$ or the $\delta 2$ position. The 5-mm diameter by $\frac{1}{4}$ " thick copper collimators at these same locations were inserted to perform the beam-tuning procedures. Of course, these assemblies were removed from the beam line during regular experimental runs. The value of having removable collimators at these positions was proven on many occasions during the course of the experiment.

The other main mechanical part—the goniometer—was controlled similarly in another LabView-CAMAC environment.

A number of power supplies were needed to drive the focusing magnets and the main sweeping magnet. We also needed to add degaussing coils and a dedicated power supply for it to obtain data in the electron-transmission mode. The power supplies were provided by NIST, except for the main power supply for the sweeping current, which was purchased. The choice of the proper power supply was dictated by the necessity to bend a 25-MeV (and possibly somewhat higher-energy) electron beam by 43 degrees. To do this, we mapped the area between the magnet's pole pieces using both rotating-coil and Hall-

effect Gaussmeters while driving the magnet at low currents. This allowed us to predict the required current to be about 58 A for 25-MeV electrons. After acquiring a 120-A power supply in order to have plenty of tolerance, we found that the applied current turned out to be exactly 58 A.

2.6. The Vacuum System

In the original design of the extended beam line, the vacuum system was intended to be completely independent and isolated from the main network of pumps maintaining the vacuum in MIRE. We achieved that goal by installing two isolating valves on either side of the goniometer. However, our second goal, which was to isolate the goniometer, was not achieved, since we could only obtain one turbo pumping station to pump down the entire extended beam line. In the course of the experiment this limitation proved to be a severe handicap, since quick changing of samples was not possible. We had to plan our runs such that each sample replacement was done at the end of the day, so that the pump-down process could be performed properly. The most time-consuming part of the process was waiting for the turbo pump to stop before venting the line, which requires 2 hours.

The normal operating pressure is approximately 4×10^{-6} Torr. Both an ion gauge and a conventional thermocouple gauge are used for the vacuum monitoring.

2.7. Tuning Procedures

The two modes of operation for the experiment are the electron-transmission mode and the photon-radiation mode. In the electron-transmission mode the HP-Ge detector is masked by a movable lead shielding wall and a lead brick placed immediately in front of and blocking the lead collimator upstream of the detector. The channeled electrons then are observed with two plastic scintillators in a button-and-paddle assembly. In this mode the orientation of the crystal is varied to map the crystal and find its axis. This is done by means of iterated scans along two different angular directions, namely along θ (the polar angle about the vertical axis) and along ψ (the polar angle about the horizontal axis perpendicular to the beam direction). Our initial scans with a silicon crystal led us to observe the famous W-shaped transmission spectra, an example of which is shown in Fig. 3. In fact, observation of our first W spectrum was so encouraging that we decided to run a complete set of scans to map the silicon crystal before actually looking for channeling radiation. This fortunate decision enabled us to understand the later radiation spectra even in the face of large backgrounds from the slits.

In the photon-radiation mode, the detection system consists of a liquid-nitrogen-cooled high-purity-Ge detector and a dedicated PC-based data-acquisition system. A similar series of scans is performed with a crystal that had been mapped in the previous mode, in order to observe a statistically detectable peak around a particular crystal axis or

plane. Again, our preliminary experiments with the silicon crystal were so promising that we decided to continue, in spite of the background problems.

In order to obtain good data, the beam quality needs to be the best that is achievable by the machine. This is done by a series of tuning runs, in the following order:

- maximizing the beam current passing through $\delta 1$ (with $\delta 2$ out);
- maximizing the beam current passing through $\delta 2$ (with $\delta 1$ out);
- maximizing the beam current passing through both $\delta 1$ and $\delta 2$;
- observing the beam shape and size on both screens.

During the tuning process the beam shape was checked periodically by placing the fluorescent screens in the beam line. The beam current was monitored by conventional plastic-scintillator detectors and a 4" cubical aluminum block. With our best alignment we were able to achieve 35% transmission through both collimators.

The alignment and tuning are very important parts of the experiment, since meeting the critical-angle-requirements is the key to successful channeling. In fact, we were continually refining our tuning skills up to the termination of the project.

2.8. The Goniometer

The most important piece of mechanical equipment in a channeling-radiation experiment is the goniometer. The angular resolution of the definition of the axis and the planes of a crystal is only as good as the mechanical resolution of the goniometer. In this experiment, rather than purchase a new goniometer, which would have cost about \$40K, we obtained the old three-axis goniometer from Stanford that had been used in the pioneering experiments on channeling radiation that had been carried out in the late 70s and early 80s at Livermore. Unfortunately, however, this goniometer required considerable effort to get it to function. At first we had vacuum leak problems, which were resolved only after laborious mechanical work was done. After installation we found that the θ motion is not entirely reliable, and serious backlash problems were a major inconvenience. These problems had to be addressed by following a series of mechanical procedures before doing angular (or linear) scans.

The goniometer is capable of four movements: θ (about the vertical axis normal to the beam line), ϕ (the azimuthal angle, about the beam-line axis), ψ (about the horizontal axis normal to the beam line), and Z (vertical linear motion). All movements are driven by stepping motors controlled in a LabView-CAMAC environment.

A LabView program was written to control the entire set of stepping motors, which included the collimator/viewing-screen assemblies. The program includes a complete series of controls over the number of steps and the stepping frequency for each motor. A special feature was added later to provide for repetition of the stepping process in designated periods (e.g., 50 steps in every 10 seconds). This provides the possibility of

performing slow scans, which is normally not possible, since the stepping frequency can be slowed only down to 20 Hz.

LabView is able to control the CAMAC bus controller through a special PC card purchased from Kinetic Systems. Six stepping-motor controllers (from Kinetic Systems) then communicate with the program, and send stepping signals to the special stepping-motor power supplies, also manufactured by Kinetic Systems. Power and control signals were connected to the stepping motors via a patch panel.

The crystal samples were mounted on a special multifunctional sample holder that was capable of moving the sample in and out of the electron beam by a rotation of 90° in the ϕ direction.

2.9. The Detector

The HP-Ge Detector was manufactured by Ortec, as were the electronics and data-acquisition systems. The detector's effective size is about 36 mm in diameter; its exact thickness is not known, but it appears to be between 5 and 7 mm, since it is most efficient in the range of photon energies between 10 and 100 keV, spanning very nicely the photon energy that we are most interested in, namely, 33 keV, the location of the K-edge in iodine. The photon detector is used in the photon-radiation mode of operation. The detector signals are amplified near the detector, then reshaped in the control room, before feeding the electronic logic units necessary for the PHA and MCS modes of data acquisition.

The Dewar that is attached to the detector was designed for field work and is inconveniently small, being capable of cooling the detector for a period of only six hours. Moreover, MIRF is operated by only two persons, and only during the day shift. Therefore, the cooling process had to be started a few hours before an experimental run, and it was not possible to keep the detector in an operational condition at all times. This was yet another operational handicap encountered during the course of the experiment.

3. The Experiment and Results

In spite of the low counting rates resulting from the low pulse-repetition frequency of MIRF (only 120 Hz) and the large background contaminations due to the visibility of the energy-analysis slits by the detector and to the necessity of mounting the entire experiment in the same room as the accelerator, we were able to align a silicon crystal and observe axial channeling radiation. The signal-to-noise ratio for channeling radiation was better than 2:1, while a comparison of the bremsstrahlung spectrum obtained with the crystal in a random orientation with the axial channeling-radiation spectrum yielded results that were substantially different. The measurements were performed in three steps:

- 1) mapping the crystal using the transmission technique (with electrons), in search of its main axis and planes;
- 2) scanning the crystal along the ψ and θ directions using the radiation spectrum, to find the axis, where we expect the maximum radiation intensity;
- 3) acquiring the radiation spectrum in both on- and off-axis orientations.

For the case of silicon we investigated the crystal thoroughly, and found the axis and the planes, which eventually led to the observation of a channeling-radiation spectrum that was 100% above the noise level, compared with a near-axis bremsstrahlung spectrum that was only 20-30% above the noise level. However, we could not reproduce similar results for diamond, due to the unexpected termination of the project. The entire tuning process would have had to be redone for the diamond sample, which is a tedious and time-consuming process.

Figures 3-9 show our results. Figure 3 shows the results of a ψ scan with the silicon crystal as a multi-channel scaler (MCS) plot, where the famous "flying W" can be easily recognized. The corresponding scan in the θ direction, shown in Fig. 4, confirms the position of the axis. These figures show how electrons are being channeled and consequentially producing more photons. Similar scans in the radiation mode, Figs. 5 and 6 for the ψ and θ directions, respectively, show how the photon counting rate increases near the axial direction. Figures 7 and 8 show the corresponding pulse-height analyzer (PHA) spectra in the on- and off-axis crystal orientations, respectively, confirming the strong presence of channeling radiation. Finally, the difference spectrum, corresponding to the channeling radiation alone, is shown in Fig. 9.

4. Contributions

Many of the parts, all of the design, and the great bulk of the installation was purchased or carried out by SFA staff and consultants. In addition, however, a significant number of items, some quite substantial, were provided by the following contributors:

- The George Washington University (Physics Department):
 - plastic scintillators and photomultiplier tubes;
 - stepping-motor power supplies;
 - machine shop services;
 - NIM electronics;
 - CAMAC electronics;
 - goniometer (through Stanford University);
 - assortment of crystals and crystal holders (through Stanford University).
- NIST (Ionizing Radiation Division):
 - vacuum parts and high-vacuum pumping system;
 - assortment of mechanical parts;
 - installation services;
 - personal computer for experiment control;
 - electrical wires, electronic parts, *etc.*;
 - video monitoring system;
 - focusing magnets;
 - alignment laser;
 - not least, the use of MIRF.
- AFFRI:
 - assorted vacuum parts.
- Naval Research Laboratory:
 - sweep magnets;
 - power supplies.
- Naval Surface Warfare Center:
 - HP-Ge detector;
 - data-acquisition hardware (personal computer);
 - data-acquisition software.

We appreciate the loan of this equipment and the provision of these services, without which the experiment would not have been possible.

5. Conclusions

We maintain our original assessment that the technical risk in showing commercial feasibility of channeling radiation applications is reasonable, given access to the proper tools (e.g. state-of-the-art high intensity, low divergence electron beam facilities). Unfortunately, generating these capabilities independently was well beyond the scope of this Phase II study. While we remain convinced that the conceptual approach identified under Phase I of this study is viable, we now realize the difficulties in aligning the necessary resources to reduce the concepts to practice. Our initial momentum and considerable resources were dissipated in a search for access to a well-suited accelerator facility. Dynamics across the accelerator community during recent years have forced the de-commissioning of many facilities and stressed those that have remained operational.

In the end, we were fortunate to gain access to the facilities at the Medical Radiation Effects Facility at NIST. But this came late in our project, the facility was not optimal, and we were fortunate to progress as far as we did in the closing months of the contract. In the end, we succeeded in demonstrating characteristics important for applying channeling radiation, but did not achieve sufficient x-ray exposure levels to reach our goals.

In the period which elapsed between the Phase I study and the conclusion of the Phase II effort, technology advances occurred in the areas we had targeted for commercial applications. Especially in the area of micro-lithography within the semiconductor industry, advances in the application of optical and ultraviolet wavelengths allowed commercial development of deep-submicron capabilities without the need for x-ray lithography. Such advances obviously affected the potential market for the capabilities our project sought to provide, and we were not able to identify a partner to enter into a Phase III activity.

SFA, Inc. is extremely grateful for the opportunity provided to us by the Department of Energy in allowing us to pursue business opportunities in the application of channeling radiation. At present, we have not demonstrated feasibility to the point that we can either gain the interests of a business partner in this area or enter into product development independently.

Figure 2

Figure 3

Psi Scan - Si Sample (Transmission Mode)

Figure 4

Theta Scan - Si Sample (Transmission Mode)

Figure 5

Figure 6

Figure 7

Radiation Spectrum from Si (ON-Channel)

Figure 8

Radiation Spectrum from Si (OFF-Channel)

Figure 9

ON- minus OFF-Channel Spectrum from Si Sample