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User's Guide: An Enhanced Modified Faraday Cup for the Profiling of the Power Density Distribution in Electron Beams

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U.S. Department of Energy

Lawrence Livermore National Laboratory

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VERSION 1.0

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PREFACE

This handbook describes the assembly and operation of an enhanced Modified Faraday Cup (MFC) diagnostic device for measuring the power density distribution of high power electron beams used for welding. The most recent version of this diagnostic device,[1] Version 2.0, contains modifications to the hardware components of previous MFC designs.[2] These modifications allow for more complete capture of the electrons and better electrical grounding, thus improving the quality of the acquired data and enabling a more accurate computed tomographic (CT) reconstruction [3,4] of the power density distribution of the electron beam to be performed.[5-9]

Hardware and software packages are being shipped to the following locations during 2002:

1. BWXT Y-12 Plant (Contact: Tom Mustaleski)
2. Kansas City Plant (Contact: Jim Dereskiewicz)
3. Los Alamos National Laboratory (Contact: John Milewski)
4. Sandia National Laboratory – Livermore (Contact: Chuck Cadden)

It is our goal to help incorporate these new software and hardware changes into this system to allow easy transferability of data between the DOE facilities in the out years of this program. The users are therefore encouraged to contact LLNL with suggestions for improvements to the MFC beam profiling system.

BASICS OF ELECTRON BEAM DIAGNOSTICS

The inability to characterize and control the focus of electron beams used for welding has been the limiting factor in transferring welding parameters between different machines and different facilities. Without the use of diagnostic tools, the focusing of electron beams has been a subjective process relying on operator control to reproduce optimum weld focus settings. Such a subjective parameter makes the repeatability of welds difficult, especially with different machines and operators performing the same weld. In response to this need, LLNL has developed a beam profiling device which can rapidly measure not only the size and shape, but also the power density distribution of an electron beam.

LLNL's beam profiling device uses a modified Faraday cup (MFC) technique coupled with a fast data acquisition system to sample the electron beam at multiple radial angles to determine the size and shape of the electron beam. In order to acquire the data, the on-board deflection coils in the electron beam welder sweep the beam at a constant frequency in a circle of known diameter over a tungsten slit disk contained within the MFC. The majority of the beam's current is intercepted by the tungsten disk and is conducted by a copper heat sink to ground.

However, when the beam passes over a slit, a portion of the beam current passes through the slit and into the Faraday cup where it can be measured as a voltage drop across a known resistor using a fast sampling analog to digital (A/D) converter. After passing over the 17 radially-positioned slits machined into the disk, a waveform containing 17 peaks is captured and stored on a personal computer. This waveform is digitally filtered, if necessary, and used to CT reconstruct the power-density distribution of the beam. The data are then fed into a computer assisted tomographic imaging (CT) algorithm to reconstruct the power density distribution of the beam.

Electron Beam Diagnostic Hardware

Figure 1 shows a schematic drawing of the latest version of the enhanced MFC device. The primary components of the enhanced MFC device are identified in this figure and include a copper Faraday cup within an electrically insulating ceramic cup, a tungsten disk containing 17 slits, and a cylindrical copper heat sink that holds the tungsten disk above the Faraday cup. A BNC type electrical connection is used to connect the MFC to the data acquisition system. In order to capture as much of the beam as possible, several features are included in the MFC design. For example, an additional slit disk, made of copper, is present on top of the internal Faraday cup to help prevent backscattered electrons from leaving the Faraday cup. A graphite ring is also added below the copper slit disk to minimize the amount of backscattered electrons that pass through the slits. In addition, an internal beam trap inside the Faraday Cup provides better containment of the electron beam when the full beam current is being measured through the center hole of the MFC. The bottom of the beam trap is protected by a graphite disk to help prevent melting and erosion of the Faraday cup base.

The most visible of these components is the tungsten slit disk (38-mm diameter, 2.5-mm thick), which contains 17 slits equally spaced at 21.18 degrees and is shown in Figure 2. It is manufactured by electro-discharge machining (EDM) using a 0.1-mm-diam wire, which produces a slit width of approximately 0.11 mm. One of the 17 slits in the tungsten disk is machined wider than the others (0.15 mm) to provide one wide beam profile in the captured waveform, which indicates the beam orientation with respect to the operator. A small hole machined on the outside rim of the disk through the wide slit also aids in providing proper alignment of the wide slit with respect to the heat sink body.

The tungsten slit disk also contains several additional features which enhance the performance of the enhanced MFC device. First, a 3.0-mm-diameter hole is machined through the center of the disk to allow a sharply focused beam to pass unimpeded directly into the Faraday cup for the full beam current to be measured. To improve grounding of the tungsten slit disk, a 0.5 mm diameter tantalum wire is vacuum-brazed to the tungsten slit disk and then attached to the copper heat sink body. This provides a low resistance electrical path from the tungsten slit disk to ground in case the copper clamp and/or heat sink body become oxidized with repeated use.

Data Acquisition and Computed Tomographic Imaging

Data acquisition is performed using a data acquisition device and a personal computer running LabVIEW software [3,4]. The data is acquired as an analog voltage signal, which is converted into a digital signal with the A/D converter sampling at high frequency. This produces a wave-form containing 17 peaks (one peak for each slit), which is then CT reconstructed using LLNL developed LabVIEW based codes [10]. Further details of the data acquisition system will be discussed in detail in a later section.

Once the data have been properly acquired, a reconstruction algorithm then separates the individual beam profiles, normalizes the areas under the peaks, filters the data, if necessary, creates a sinogram from the series of profiles, CT reconstructs, and finally calculates the beam power density distribution. A 128 × 128 pixel reconstruction of this beam takes approximately 10 s to perform and display on a Pentium-based personal laptop computer. The raw beam profiles and reconstructed beam power density distributions can then be saved on the computer hard drive and/or printed for quality control documentation purposes.

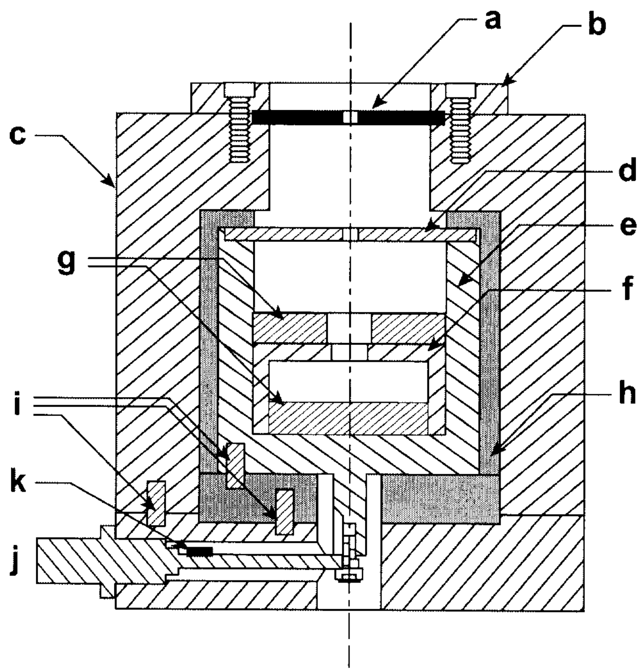


Figure 1. Cross sectional illustration of the enhanced MFC diagnostic. a) tungsten slit disk, b) copper hold-down clamp, c) copper heat-sink body, d) internal copper slit disk, e) copper Faraday cup, f) copper beam trap, g) graphite beam stops, h) insulator cup and base, i) alignment pins (not all pins are shown), j) BNC connector, and k) Zener diode.

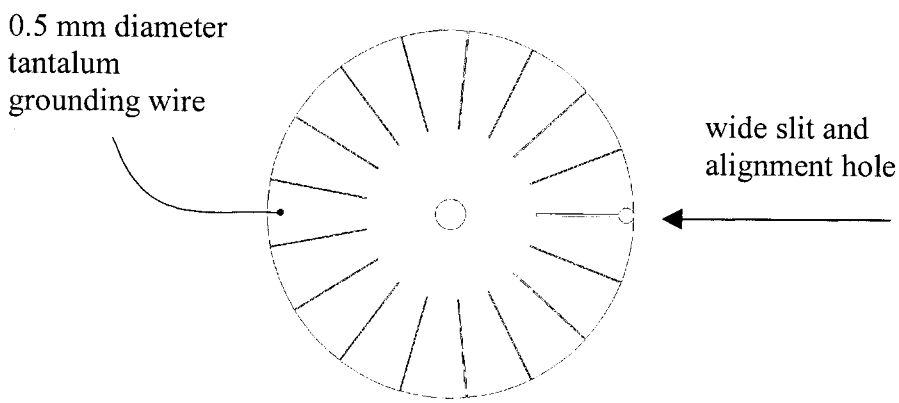


Figure 2. Illustration of the original slit disk where one slit is machined to be approximately 1.5 x wider (0.15 mm) as the remaining 16 slits, but all slits are equally spaced at 21.18 deg. The small hole located at the edge of the wide slit is used to align the wide slit in the MFC diagnostic. The 0.5 mm tantalum wire is vacuum brazed to the tungsten disk directly across from the wide slit using a high temperature brazing alloy.

HARDWARE ASSEMBLY

The enhanced MFC assembly is comprised of 14 basic components. A photograph of all of these components is shown in Figure 3(a). A complete list of the components in the enhanced MFC assembly is given in Table I.1 in Appendix I. In the table, the unique model number and quantity of each component are listed along with the component names and the sub-assembly to which each component belongs. The miscellaneous parts listed here consist of the screws and dowel pins needed to assemble the enhanced MFC. In addition, each enhanced MFC assembly comes with a set of tools, which are also listed in Table I.2 in Appendix I, required for the assembly and disassembly of the MFC. No additional tools are required. Additionally, a resistor box that allows the operator to switch between five resistances of nominal values 50Ω, 100Ω, 250Ω, 500Ω, and 1000Ω is included as part of the enhanced MFC diagnostic system. A photograph of the resistor box is shown in Figure 3(b). The design of the box insures that the input always sees a resistance of 1000Ω or less, even when the box is being switched between resistances. A 10V Zener diode in parallel with the resistance has been added to prevent the voltage seen across the resistors from exceeding a safe value.

Assembly Procedure

Each user will receive a pre-assembled enhanced MFC. However, if repair or replacement of any component in the device is required, the following assembly procedure should be used. For simplicity of design, the overall assembly is divided into three sub-assemblies: the heat sink, the beam trap, and the insulator cup. Exploded views of the three each sub-assemblies are shown in Figures 4 to 6. The name of each component used in the instructions below matches that used in Figures 4 to 6 and in Tables I.1 and I.2.

Beam Trap Sub-Assembly

1. Place the Graphite Disk (BTA-3BT-004) in the Beam Trap Body (BTA-BTB-002) and let it fall to the bottom.

   a. Turn over the Beam Trap Body and lay it on a flat surface so the Graphite Disk sits flush with the top of the Beam Trap Body.

b. Secure the Graphite Disk in Place by inserting the Hex Head Cup Pt. Set Screw, 4-40x3/32" (HHCS-440-0094) in the threaded hole on the side of the Beam Trap Body.

2. Place the Beam Trap Body in the Faraday Cup (BTA-3FC-001) with the Graphite Disk facing the bottom of the Faraday Cup. The Beam Trap Body should be seated against the bottom of the Faraday Cup.

3. Once the Beam Trap Body is seated, secure it in place by inserting a Hex Head Cup Pt. Set Screw, 4-40x1/4" (HHCS-440-0250) into the lower threaded hole on the side of the Faraday Cup.

4. Place the Beam Stop (BTA-3BS-003) on top of the Beam Trap Body inside the Faraday Cup. Secure it in place by inserting the other Hex Head Cup pt. Set Screw, 4-40x1/4" (HHCS-440-0250) into the upper threaded hole on the side of the Faraday Cup.

5. Place the Dowel (BTA-SD1-006) into the larger, non-threaded hole on the top lip of the Faraday Cup with the thin end up. It should seat in the bottom of the hole, with only a small portion of the Dowel sticking out.

6. Place the Copper Slit Disk (Equal Angle) (BTA-CSD-005) on top of the Faraday Cup.

a. Make sure that the countersunk hole in the top of the Copper Slit Disk is facing up and that it matches with the threaded hole beside the Dowel on the Faraday Cup.

b. The Dowel should fit into the slit adjacent and to the left of the countersunk hole.

c. Screw the Slotted Flat Head Screw, 2-56x.187" into the threaded hole to secure the Copper Slit Disk on the top lip of the Faraday Cup.

Heat Sink Sub-Assembly

7. Insert BNC Connector (HSA-BNC-005) into the Heat Sink Base (HSA-3BA-002). Use the 7/16"-1/2" Combination Wrench to tighten the nut behind the BNC Connector. Insure that the hole at the end of the assembly opposite to the BNC connection lies in a plane parallel to the bottom of the Heat Sink Base.

8. Place the two Dowel Pins, .125"x.375" into the proper holes in the Heat Sink Base, one in the recessed portion and the other in the raised outer lip. These two holes are the only holes which are not through thickness holes in the Heat Sink Base, and the only two into which the Dowel Pins fit.

9. Place the Insulator Base (ICA-IB2-002) on top of the Heat Sink Base with the Dowel Pin in the recessed portion matching with the proper hole in the bottom of the Insulator Base. There is a hole on each side of the Insulator Base, but only one matches up with the Dowel Pin on the Heat Sink Base.

10. Place the remaining Dowel Pin, .125"x.375" into the hole on the top of the Insulator Base.

11. Fit the completed Beam Trap Assembly onto the top of the Insulator Base; fitting the Dowel Pin into the matching hole in the bottom of the Faraday Cup in the Beam Trap Assembly.

12. Fit the Insulator Body (ICA-IB1-001) over the Beam Trap Assembly.

13. Place the Heat Sink Body (HSA-3BY-001) over the top of the Insulator Body. It should match up with the Heat Sink Base. The Dowel Pin placed in the outer lip of the Heat Sink Base should match up with the hole placed in the bottom edge of the Heat Sink Body. Even though there are a number of holes in this location, this is the only one that matches the size of the Dowel Pin.

14. Turn the assembly over to expose the bottom of the Heat Sink Base, being careful because the assembly is not firmly held together at this time.

   a. With the bottom exposed, connect the BNC Connector into the bottom of the Beam Trap Assembly using a Socket Head Cap Screw, 4-40x1/4" (SHCS-440-0250).

   b. Secure the Heat Sink Base to the Heat Sink Body using the six Socket Head Cap Screws, 4-40x3/4" (SHCS-440-0750).

15. Turn the assembly back over into its normal orientation and insert the Dowel Pin, .0625"x.187" (DPAA-625-187) into the hole on the top of the Heat Sink Base in the center recessed ring.

16. Carefully place the Tungsten Slit Disk (HSA-WWA-003) into the recessed ring on the top of the Heat Sink Body. The hole in the Tungsten Slit Disk should match up with the Dowel Pin in the Heat

Sink Body and the brazed tantalum wire attached to the Tungsten Slit Disk should be pointed towards the screw hole on the side of the Heat Sink Body

17. Place the Flange Clamp (HSA-FCA-004) over the top of the Heat Sink Body with the tantalum wire attached to the Tungsten Slit Disk directed through the channel machined into the bottom of the Flange Clamp. Once the Flange Clamp is oriented properly, secure it using the six Socket Head Cap Screws, 4-40x3/8" (SHCS-440-0375).

18. Secure the tantalum grounding wire to the side of the Heat Sink Body with a Socket Head Cap Screw, 4-40.1/4" (SHCS-440-0250).

19. The enhanced MFC assembly is placed onto the Baseplate (HSA-3BP-006), with the BNC connector located over the portion of the Baseplate with the lip removed. This section of the Baseplate allows more ease of movement of the enhanced MFC and the BNC connector.

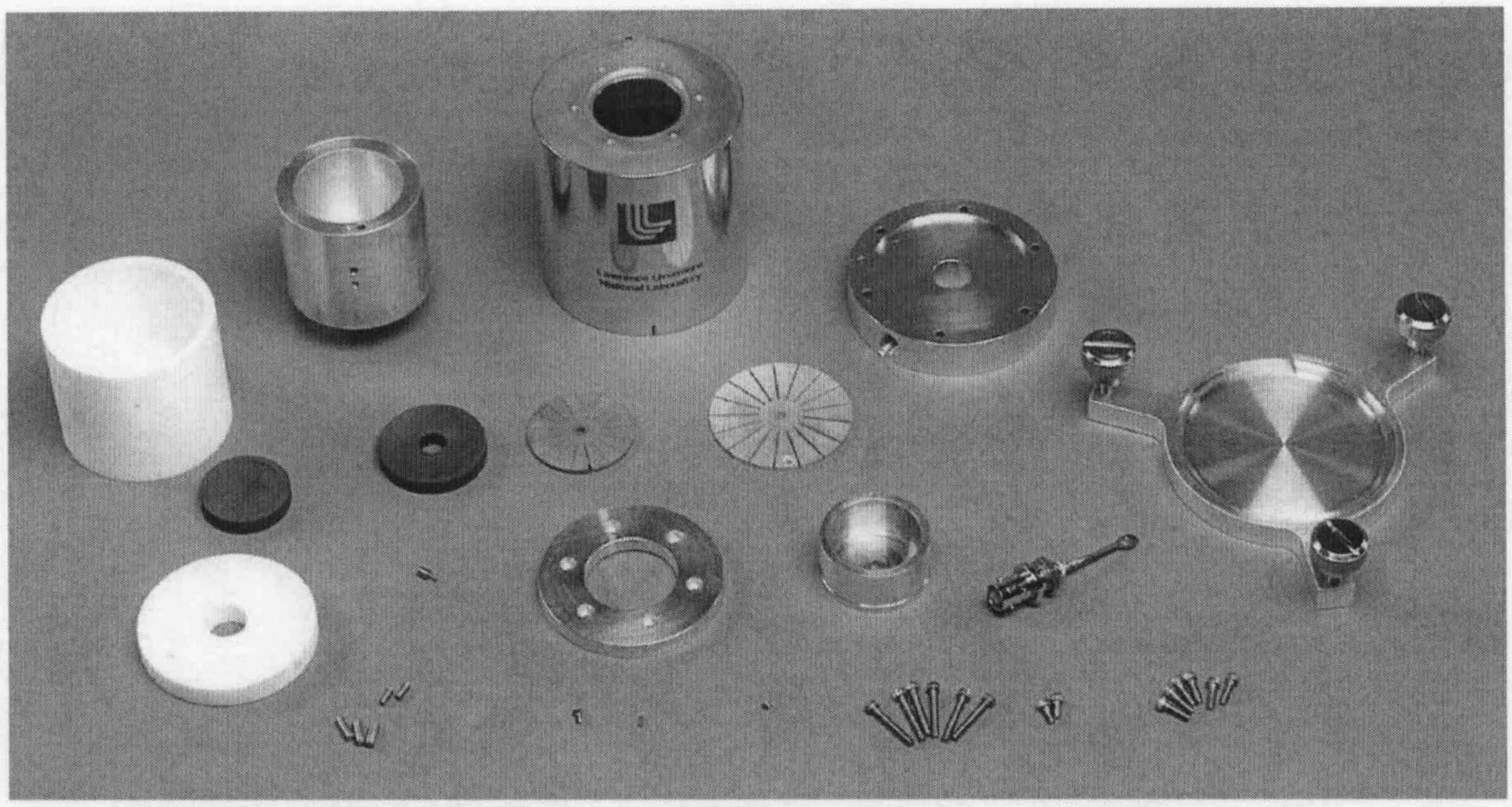
20. The enhanced MFC diagnostic is now ready for use.

** The final assembly should have the BNC Connection seated at an angle of approximately 15° to the right-hand side of the LLNL logo. In addition, the witness mark located underneath the LLNL logo should be lined up with the wide slit on the Tungsten Slit Disk. This witness mark has been added to aid the machine operator in more easily determining the orientation of the beam with respect to the enhanced MFC diagnostic device.

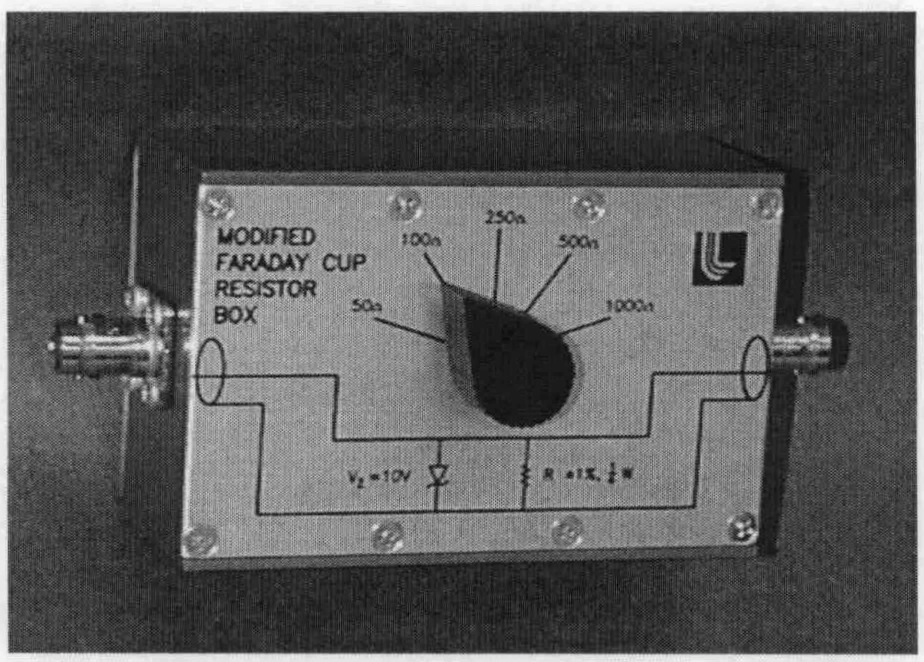
SPECIAL NOTE

Handling and Care of Tungsten Slit Disks

The Tungsten Slit Disks (HSA-WWA-003) are extremely fragile, and great care must be taken in handling them. Do not drop these parts or try to force them into the Heat Sink Body during installation. The tungsten is very brittle and cracks very easily. Falls of even several inches could result in a fracture of the disk. Once broken, the disks are irreparable. Since the disks are so delicate, three (one in the cup and two spares) are included in the initial package. An engineering drawing is also included in Appendix III to allow each location to fabricate additional tungsten disks locally.



(a)



(b)

Figure 3(a&b). (a) Photograph of the disassembled Modified Faraday Cup and (b) photograph of the resistor box.

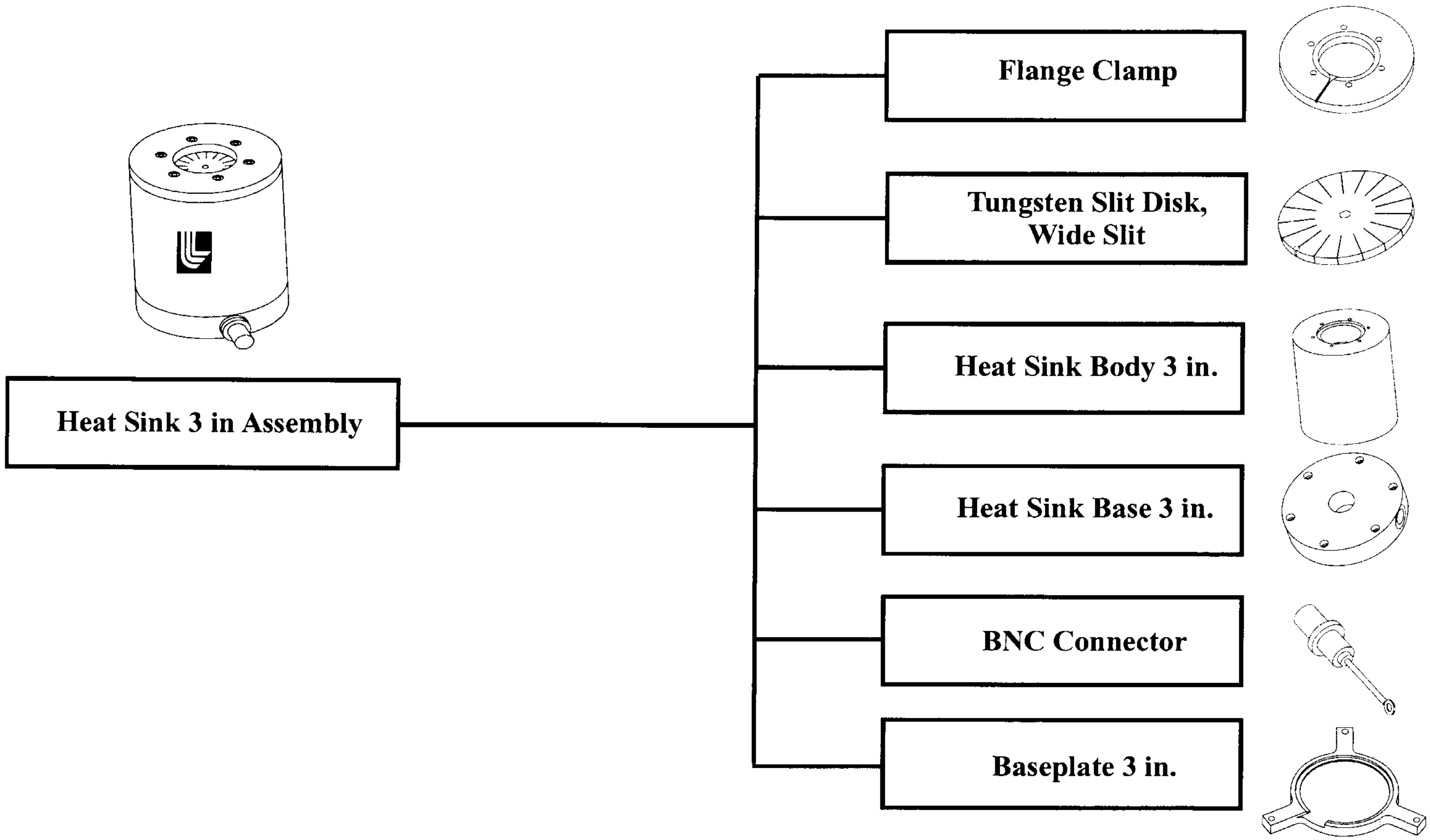


Figure 4. Exploded view of the components in the Heat Sink Sub-Assembly.

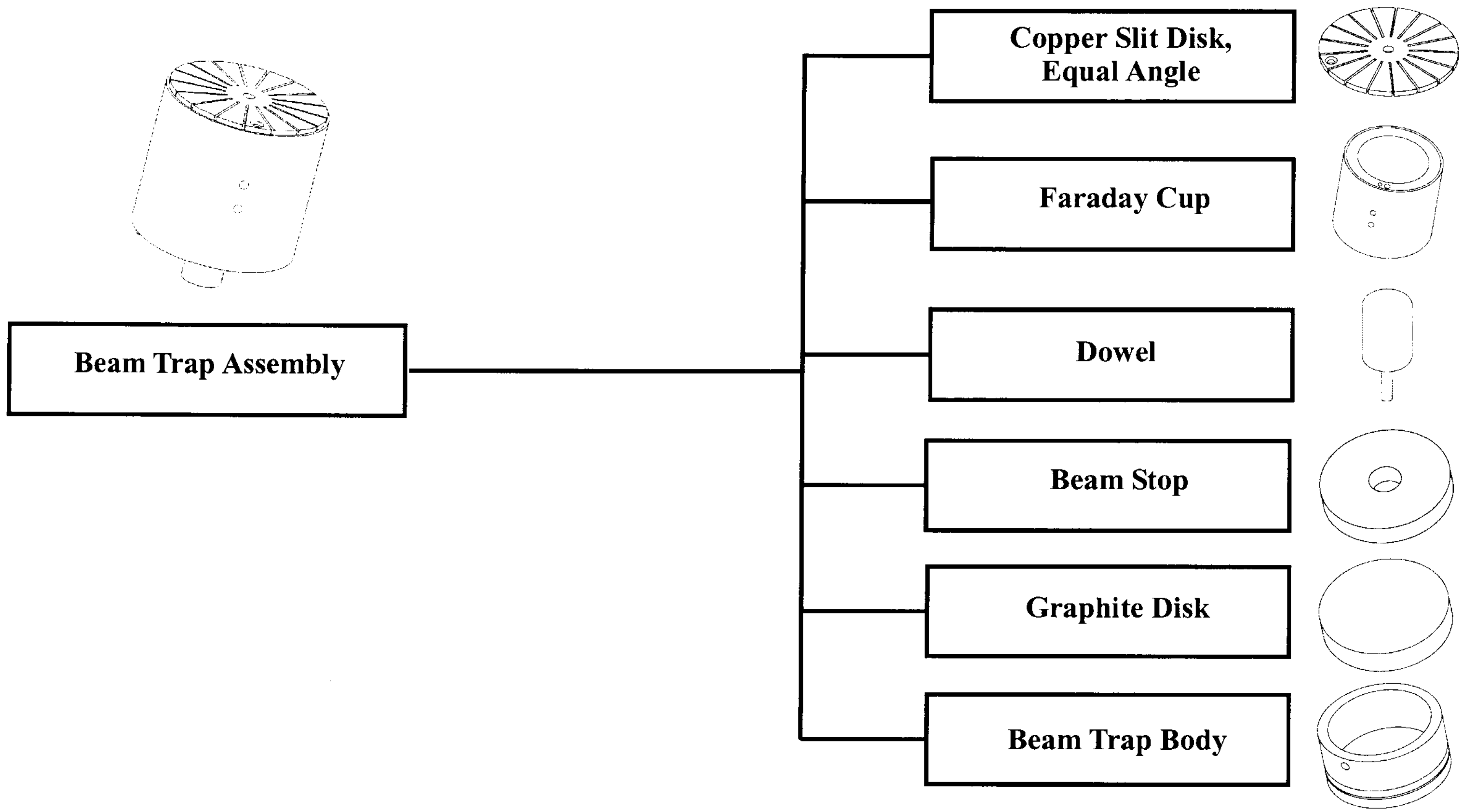


Figure 5. Exploded view of the components in the Beam Trap Sub-Assembly.

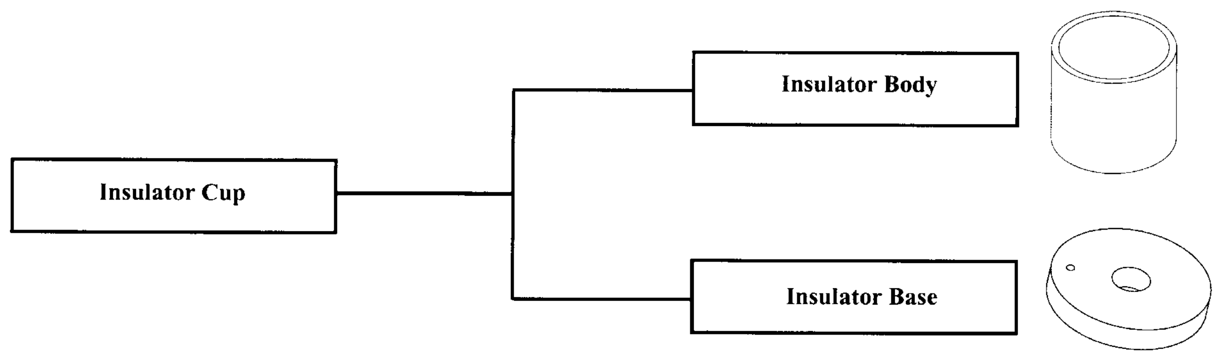


Figure 6. Exploded view of the components in the Insulator Cup Sub-Assembly.

ELECTRON BEAM WELDER SET-UP AND OPERATION

Electron Beam Welder Preparation

The MFC diagnostic is designed for use inside any electron beam welding vacuum chamber. It is set up with one BNC electrical connection (RG58 cable) that needs to be fed through the vacuum chamber wall and into the data acquisition system. Most electron beam welders are equipped with a BNC feedthrough, but if your machine is not, then you will need to fabricate a new one for this electrical connection. It is recommended that you have at least two BNC feedthroughs available, one for the MFC and one for a conventional Faraday cup. The presence of two feedthroughs may prove beneficial since it is sometimes useful to compare the full beam current through both devices during the same pumpdown.*

The largest sources of error encountered in the operation of the MFC diagnostic involve the pick-up of stray electronic noise from the electron beam welder. Several types of electronic noise can appear in the MFC waveform signal during operation if the electron beam welder is not properly grounded. For example, a low frequency multiple of the house power (60 Hz in USA), resulting in the beam profile peaks undulating up and down with time, can be observed. Electrical noise in the data can also be picked up from the improper grounding of the stands used to support the MFC diagnostic. Electrical ground loops can also create severe problems as well. Another potential noise source may appear in the form of a high frequency noise from the high voltage transformer, resulting in spikes being superimposed on the individual beam profiles. All sources of noise must be minimized or eliminated in order to achieve reproducible beam profiling results.

It is, therefore, recommended that an electrical engineer be on hand when you first begin to use the MFC diagnostic to help track down and eliminate these problems.

* Some electron beam machines have a directly built-in "Faraday cup" circuit. This circuit varies from machine to machine, and the varying characteristics of the circuit affect the enhanced MFC device in unknown ways. It is, therefore, recommended that you bypass this circuit entirely when using the LLNL enhanced MFC device. Rather, the BNC connection should be directly connected into the LLNL data acquisition system. By doing so, the potential that unwanted electrical noise will be picked up from the "Faraday cup" circuitry is eliminated.

Setting up MFC diagnostic in the Electron Beam Chamber

Figure 7 shows a schematic illustration of the set up of the enhanced MFC diagnostic device inside a typical electron beam welder and the connection between it and the data acquisition system. Using this figure as a guide, the steps to be followed in setting up the enhanced MFC device in the electron beam chamber are given below:

1. Before setting up the diagnostic device in the chamber, the distance from the top of the chamber to the weld surface (working height) must be measured.

2. Place the MFC diagnostic on its baseplate inside the chamber so that the top of the tungsten slit disk is at this measured working height. In order to reach this height, the enhanced MFC device may need to be placed on a second leveling stand, not shown in Figure 7.

   Note that the top of the tungsten slit disk is below the top of the MFC diagnostic. Ensure that the measurements of the working height are made to the tungsten slit disk surface and not to the top of the flange clamp.

3. Rotate the MFC diagnostic so that the LLNL logo and the small vertical scribe mark at the base of the MFC diagnostic directly face the operator. This alignment will place the wide slit at a position directly facing the welding operator.

4. It is highly recommended that a solid tungsten focusing target be placed inside the chamber for set-up and operator/MFC diagnostic focus comparisons. Place the top of the tungsten target at the same working height as the enhanced MFC device. It may be necessary to place a shield between the target and the MFC to prevent spatter from the tungsten target onto the MFC slit disk if high power beams are going to be inspected.

5. An optional sacrificial target made of aluminum or stainless steel, for example, can also be placed at the working level height. The purpose of the sacrificial target is to 'burn in' a circular pattern of the electron beam so that its diameter can be measured after the diagnostic run.

6. A one inch diameter circular path for the beam is recommended for use with the enhanced MFC diagnostic. In order to ensure that the beam path meets this requirement, it is recommended that two scribe lines, one inch apart, be placed on the top of the sacrificial target. Therefore, when the operator runs a circle beam over the target, he can quickly determine, before placing the beam over the enhanced MFC diagnostic, that the circle beam is set at the proper diameter.

7. Before closing the chamber, the MFC diagnostic must be leveled using the precision level provided with the enhanced MFC device. If the tungsten slit disk is tilted with respect to the axis of the electron beam, the sides of the slits will shadow, or completely block, transmission of electrons through them, resulting in no signal being received by the diagnostic and an increased potential for irreparable damage to the Tungsten Slit Disk. Adjust the MFC using the three leveling screws on the Baseplate so that it is level within ±0.01 deg in both the X and Y directions of the chamber.

8. After leveling the MFC, re-check the tungsten target and sacrificial target heights, make sure the BNC connector is hooked up, and close the door and pump down the vacuum chamber.

Connect the MFC to the Data Acquisition System

The signal coming from the MFC diagnostic carries current in the milli-Amp range that is converted to a voltage drop across a known resistor. This voltage drop is then measured using the data acquisition system. Accompanying the MFC diagnostic is a resistor box fitted with BNC connections and containing five fixed resistors between 50 to 1000 Ω.

1. Connect the BNC cable originating from the exterior connection of the BNC feedthrough on the electron beam chamber to either side of the resistor box.

2. Choose the desired resistor on the resistor box. A resistance of 250 Ω works well for most applications.

3. Using another BNC cable, connect the resistor box to the NI DAQ board, which is then connected to the computer.

The system is now set up and ready for the data acquisition system to be activated.

Setting up the Electron Beam Weld Parameters

After the diagnostic is in place and the chamber is pumped down:

1. Position the tungsten focusing target below the beam. Turn on the beam to the desired current and voltage and determine the sharp focus position using the machine optics. Record this focus setting as the operator's best focus.

2. With the beam off, position the MFC diagnostic directly beneath the beam so that the beam is centered on the 3 mm diameter hole located in the middle of the tungsten slit disk. Turn on the electron beam and, using the data acquisition system as described below, record the full beam current. Save this data file for possible future use.

3. With the beam off, return to the tungsten focusing target. Turn on the beam and using the deflection coils of the electron beam welder, oscillate the beam in a circle at 60 Hz. With the beam oscillating, adjust the diameter of the beam to 25 mm (1"), and record the diameter adjustment setting.*

4. With the beam off, move to the sacrificial target and activate the beam oscillation coils. Then briefly turn on the beam to burn in the path of the electron beam. The exact diameter of the electron beam path will be measured on the sacrificial target after the experiment is over and will be used to fine tune the CT reconstruction results if necessary.

* This setting can be verified by moving repeating these beam settings on the sacrificial target in the location where the scribe line described above have been made.

5. Turn off the beam and move the MFC diagnostic so that it is centered below the electron beam. The diagnostic is now ready to be used to measure beam power density distributions for different focus settings at the preset beam current and voltage.

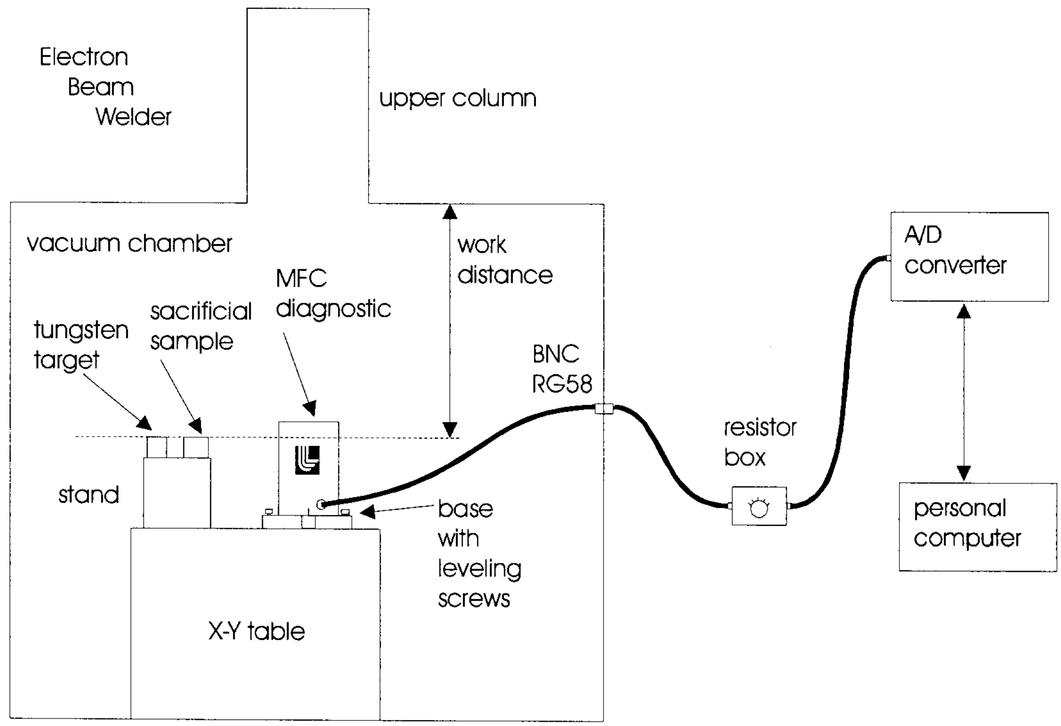


Figure 7: Schematic illustration of the MFC diagnostic setup inside the EB welder and the data acquisition components located outside the EB welder.

Some words of caution regarding the tungsten slit disks

- Handle the tungsten disks with care and be wary not to damage the slits by using high power densities.
- Start out practicing on low power beams (2 mA, 100 kV) and gradually move up from there.
- Try to take data quickly, then immediately turn the beam off as soon as the data acquisition is complete. Let the tungsten disk cool between runs.
- It is nearly impossible to say what the damage threshold will be since each machine focuses to different spot sizes; however, sharp focused beams above 10 mA at 100 kV have rapidly cut into the tungsten disk on the LLNL machine when oscillating the beam at 30 to 60 Hz.

SAFETY NOTES:
THERMAL AND ELECTRICAL HAZARDS

The modified Faraday cup is identical in operation to the standard Faraday cups that are supplied and used with all electron beam welders, except for the fact that it contains a slitted tungsten disk to sample the electron beam at various angles. As such, the MFC should be handled with the same precautions as standard Faraday cups.

Thermal Hazards

During operation, the MFC receives energy from the electron beam, which heats up the enhanced MFC device inside the vacuum chamber. The enhanced MFC device is constructed of high melting point metallic and ceramic materials that will not be damaged during use. However, the amount of energy being deposited into the MFC will raise its temperature, and care must be used when removing the MFC from the electron beam chamber. If the MFC must be removed prior to letting it cool down in the chamber, then it is necessary to use protective, non-flammable, hand wear. The MFC should then be placed on a non- flammable table, and an appropriate sign, indicating that the device is hot should be placed in plain view until the MFC cools to room temperature.

Electrical Hazards

During normal use, the electron beam current collected by the MFC takes a path to ground through the current viewing resistor. The value of this resistor is chosen to provide a voltage signal compatible with the input range of the data acquisition electronics. This is the principle commonly used by the Faraday cups that have been used to measure the electron beam current for decades.

IT IS THE RESPONSIBILITY OF THE WELD OPERATOR TO BE SURE THAT A CURRENT VIEWING RESISTOR IS CONNECTED TO ANY FARADAY CUP BEFORE THE ELECTRON BEAM IS TURNED ON.

A potential safety hazard exists if the enhanced MFC device is collecting data from an electron beam with the current viewing resistor removed from the path to ground. In this case the length of coaxial cable attached to the enhanced MFC device will act as a capacitor, and a charge will build up as electrons from the beam are collected. The voltage potential on the coaxial cable/capacitor is given by the simple equation:

$$V=Q/C \qquad (1)$$

where V is the voltage, C is the capacitance of the length of cable, and Q is the charge, which is equal to the beam current multiplied by time. The voltage can quickly reach kilovolt levels before an arc occurs at some point and the buildup is discharged. If the beam current remains on, a rapid cycle of charging and arcing will result. A shock hazard will result if personnel are exposed to the charged center conductor of the coaxial cable.

In order to prevent such an accidental buildup of charge, the new LLNL MFC design includes a built-in Zener diode (1N4740A). The anode of the Zener diode is attached to the shell of the BNC Connector assembly (HSA-BNC-005), and the cathode is attached to the center conductor of the same assembly. Since the BNC Connector assembly is screwed into the Heat Sink Base (HSA-3BA-002), the Zener diode is hidden from view. This Zener diode limits the voltage on the center conductor to less than 10 V.

The Zener diode should be tested periodically to insure that it is providing the proper protection. A procedure for completing this test is included below:

1. Using the Diode Test mode of a digital multimeter first test the forward bias by touching the positive lead to the shield and the negative lead to the center conductor. *The meter should read a forward voltage drop around 0.6 or 0.7 V.*

2. When testing the reverse bias, the meter should read open circuit or infinite resistance (OL or OverLoad on some meters).

3. Possible indications of failure include open circuits or short circuits in both directions.
    - Open circuits may be caused by a disconnected lead to the diode.
    - Short circuits may be caused by some conducting material bridging the center conductor and the base or by the metal case of the diode touching the center conductor

The source of an open-circuit failure might be determined by removing the BNC Connector assembly and inspecting the diode. The case may touch the threads of the tapped hole in the Heat Sink Base without affecting performance.

DATA ACQUISITION:
CONCEPT AND COMPUTER HARDWARE FOR BEAM PROFILING

The purpose of the data acquisition system is to rapidly sample the electron beam and store a waveform containing the raw data necessary for later CT reconstruction on the computer. The multi-angle slit disk and recent advances in computer-based data acquisition have reduced the time required to analyze a beam from hours to seconds over the period of less than a decade. With these advances, it is now possible to use the MFC and computed tomography as a near-real-time diagnostic in electron beam welding. Personal desktop and laptop computers can be used with the appropriate hardware to perform these data acquisition operations.

One hardware setup, which is being used successfully at LLNL, utilizes a fast and portable PXI configured computer, with off-the-shelf data acquisition components. This system is summarized below:

- PXI-6070E device for use in a laboratory PXI/CompactPCI system. This device is capable of 1.25 MS/s 12-bit analog input
- An NI E-series DAQ board or card is recommended, since the LLNL software does not currently support data acquisition devices from other vendors.
- The value of the current viewing resistor should be selected with the beam current and input range of the DAQ device in mind. The maximum input range on NI DAQ devices is typically ±10 V, with gains that allow voltage ranges of ±5 V, ±2.5 V, ±1 V, or smaller. Because of the direction that current flows through the resistor, the voltage read will be negative, so the DAQ device will have to be used in the bipolar mode. A resistor value between 200 and 500 Ω will allow use of the +/- 5 or +/-2.5 V ranges for most beam currents.

A secondary system is laptop-based with a DAQCard-6062E device. This device is only capable of 500 kS/s, but it fits into a laptop's PC card slot which enhances portability. While the 500 kS/s sampling rate is adequate for most beam reconstructions, a faster device can give added flexibility if the beam deflection rate must be increased. NI DAQ devices are configured using their Measurement & Automation Explorer (MAX), so any device with an adequate sampling rate should work.

Other computer configurations can be used to suit the unique needs of each facility. However, some elements must be in common with the LLNL system in order to run the LLNL written software and to acquire data rapidly enough to produce an accurate reconstruction of the beam.

The LLNL developed software is written in the National Instruments (NI) LabVIEW graphical programming language, Version 6i for Windows 2000/NT 4.0(SP3 or later)/Me/9x.* A minimum of 64 MB of RAM is required, and 128 MB is recommended. NI's system requirements only state that a Pentium processor or equivalent is recommended. However, since the tomography algorithm is computationally intensive, the fastest processor available should be used for best results.

* Even though LabVIEW is available for other platforms that could run the reconstruction software equally well, support for NI's data acquisition (DAQ) hardware is better under Windows.

USING THE MFC AS A CONVENTIONAL FARADAY CUP

The enhanced MFC device also contains a design feature which allows the beam current to be measured by collecting the full beam down the center hole in the tungsten slit disk. When operating in this mode, the enhanced MFC device is being used much the same as a conventional Faraday cup, and therefore doesn't require the full data acquisition hardware and tomography software that will be described in the next section. When the full beam current passes through the hole in the center of the tungsten slit disk, the beam trap in the bottom of the cup will collect the beam current and any backscattered electrons. As these electrons travel to ground through the current viewing resistor, the DAQ device can read the voltage across the resistor. The current is then calculated using the simple formula:

$$I = V/R \quad (2)$$

where I is the current, V the measured voltage, and R the value of the current viewing resistor.

A quick method of reading the voltage is to use the Test Panel in MAX. Step-by-step instructions for using the enhanced MFC device for measuring the electron beam current are given below:

- To open the Test Panel first open the hierarchy under "My System" in the Configuration column on the left side of MAX by clicking on the box with the plus ("+") sign in it as shown in Figure 8.
- Then open "Devices and Interfaces" in the same manner, and highlight the DAQ device.
- Right click on the device icon, and a popup menu will appear. Select "Test Panel." Select the "Analog Input" tab to bring its panel to the front (Figure 9).

  There are controls for channel number, input limits, and sampling rate. The channel number is the DAQ device channel in which the enhanced MFC device is inserted. The high and low input limits determine which gain is used on the acquisition. The maximum range is +/- 10V which has a gain of 1. Smaller ranges may be used if the expected beam current and the resistor value will produce a smaller voltage.

- To take beam data, set the "Data Mode" radio button to "Continuous" and hit the start button. When the beam is turned on, note the "Average Reading" in the center bottom. Divide this voltage by the value of the current viewing resistor to get the beam current.*

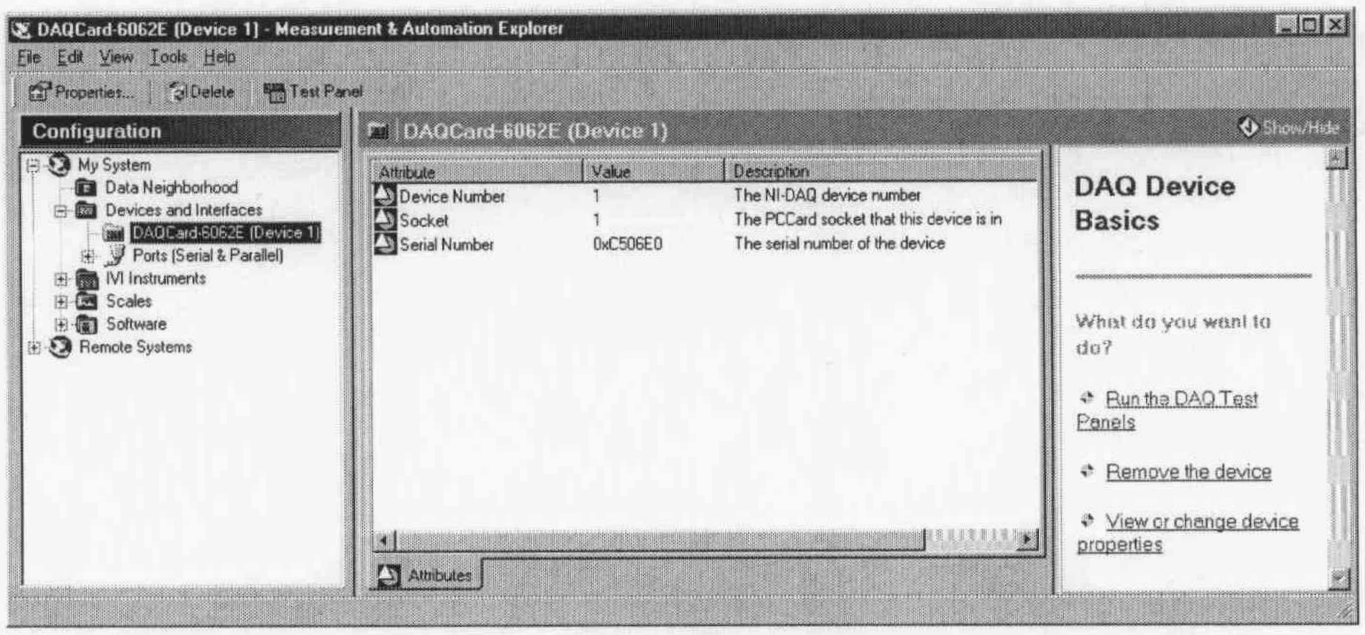


Figure 8. National Instruments Measurement & Automation Explorer (MAX) window

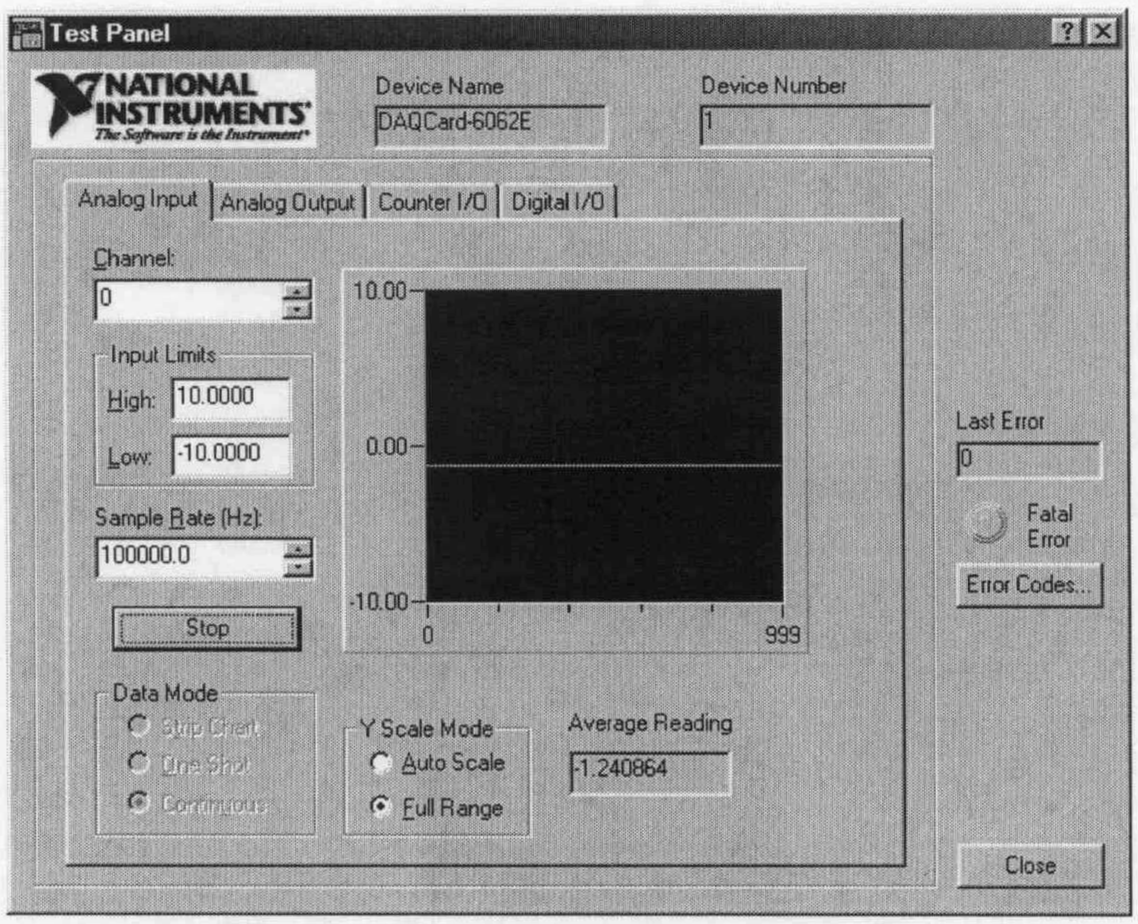


Figure 9. The Analog Input tab of the MAX Test Panel

* The "Analog Input" panel displays 1000 data points, so it may be useful to check the beam current at several different sampling rates to see if there is any high or low frequency ripple (usually harmonics of the 60 Hz power) in the beam current.

COMPUTED TOMOGRAPHIC BEAM RECONSTRUCTION

The most common use of computed tomography is in non-destructive evaluation applications, such as the internal examination of closed structures, medical diagnostics, and security screening. The internal structure of a subject is examined by determining the density distributions in a plane projected through the subject. The subject is x-rayed at a number of different angles around the plane, and a linear sensor on the other side measures the transmission of the x-rays through the object. The linear sensor produces a profile of the subject at each angle. The resulting set of profiles is then used to reconstruct the density distribution using a filtered backprojection technique[11]. By doing similar reconstructions in many parallel planes, a three-dimensional reconstruction of the object can be completed.

These same techniques can be applied to the determination of current and power density distributions for an electron beam welder, where the subject to be examined is not an object that can be probed with x-rays or other external sources, but something that can be measured directly. A technique to determine the electron beam power density has been developed at LLNL and is described in several published papers.[1-4]. In this technique, the electron beam is swept across a narrow slit placed on top of a Faraday cup at a known rate. A time history of the voltage seen across the resistor can be translated into a one-dimensional spatial profile of the beam. By taking similar profiles at a number of different angles, computed tomography techniques can then be used to reconstruct the power density distribution of the beam.

The LLNL-written software program, EB_MkTomo.exe, is an executable program that performs multiple functions including data acquisition, CT reconstruction, and file import/export functions to handle different file header formats. EB_MkTomo.exe is the only LabVIEW program you will need to acquire and reconstruct beam profile data. Figure 10 shows the major features of the program with a flow chart representation of the three major steps of the program. Step 1 encompasses the input of initial parameters to be used in the reconstruction and the initiation of the program. In Step 2, the MFC data are brought into the program by either retrieving previously taken data from a data file stored on the computer (Step 2a) or by acquiring new data in real time (Step 2b). Both Steps 2a and 2b include the ability to iteratively change some parameters and filter settings until a good sinogram is formed. The actual beam reconstruction takes place in Step 3. The user can examine the reconstruction and has the ability to save the reconstructed image to a file for use by other programs.

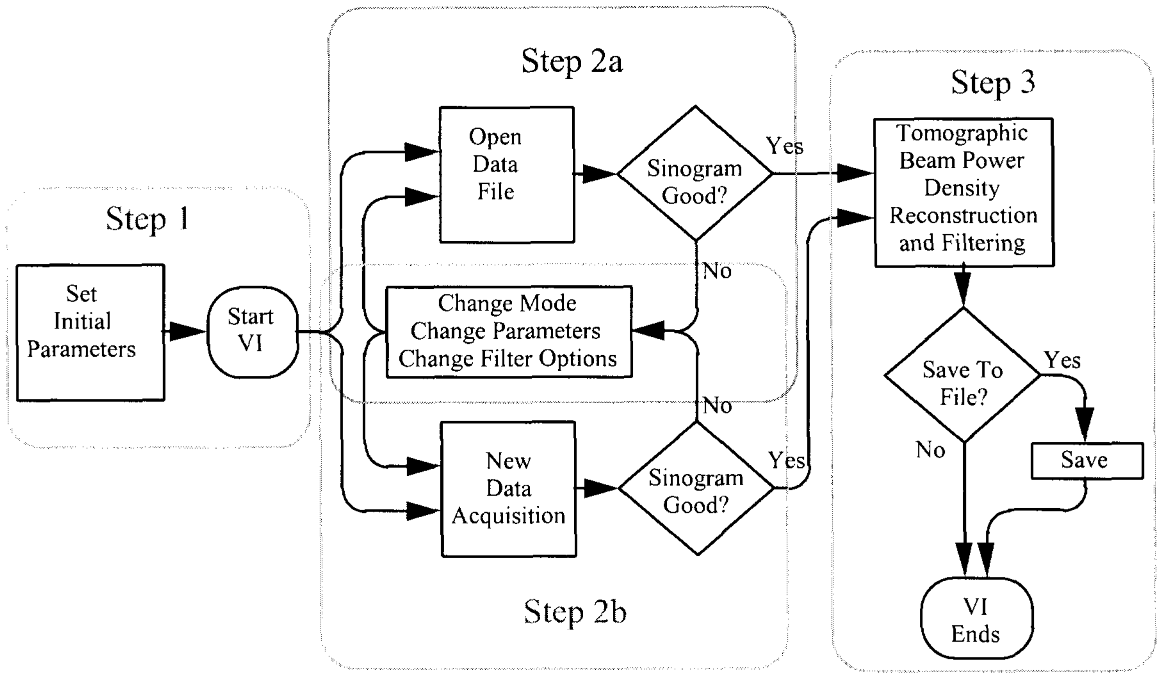


Figure 10. Flow of program EB_MkTomo.exe

When the main vi is called, it opens a sub-vi that allows the user to pick the data source. If a data file is selected, a window will open that allows the user to choose a file. If the data are coming from a file containing beam parameter header information, the beam parameters are automatically read and used in the analysis. Otherwise the user can enter the beam parameters manually. If the data acquisition option is selected, the sub-vi will use the beam parameters to determine the necessary array length and continually acquire and display arrays of data until the user sees the desired data.

The reconstruction process begins by arranging the data into a sinogram, which is the conventional way of representing all of the profile data in a single two-dimensional array. In the sinogram, the profiles taken from each slit are represented in one row or column of the array in the order of the angle of rotation. Significant features in the beam show up as bright spots in the profiles that can be seen moving from side to side as the beam is profiled from different angles.

The amplitude of the apparent movement is greater for features farther from the center of the beam. When the profiles are placed next to each other, the movement of the features look like sine wave patterns, thus giving the sinogram its name.

Data for the sinogram may be taken from a data file or acquired in real time by a DAQ device in the host computer. In both cases, the user may filter the data to reduce noise in the sinogram. It is desirable to minimize noise as early in the process as possible. For example, the computed tomography technique includes a high pass filter, which tends to amplify any noise in the data and adversely affects the beam power density calculation. The user also has the option of applying several different filters alone or in series. When the user is satisfied with the noise removal, clicking on the "Yes" response to the "Sinogram Good?" label sends the data back to the main vi for the tomographic reconstruction.

The main vi then sends the sinogram to another sub-vi for reconstruction. Depending upon the number of elements in the profiles the reconstruction can take anywhere from less than a second to 15 seconds or more. The speed of the calculation may be increased by setting the "resize factor" to a value greater than one. When a higher "resize factor" is used, the number of points equal to that value will be averaged together, decreasing the size of the profiles, and speeding up the reconstruction, accordingly, but at the expense of the resolution of the reconstructed beam. The length corresponding to each element in the array can be calculated from the sampling rate (Samples/sec), the resize factor, the circular deflection frequency (in cycles/sec), and the circular deflection diameter (mm).

The tomography sub-vi uses a filtered back-projection algorithm to create a 2-D array containing the reconstructed power distribution within the beam. The total power of the beam is the product of the beam current and the accelerating voltage. The area of each element or pixel in the 2-D array is the square of the length corresponding to an element in the beam profiles. The power density of the beam is calculated by normalizing the two-dimensional reconstruction of the beam to the beam power and the element area.

On the other hand, the filtered back-projection technique can introduce features called "artifacts," which are radial ridges and valleys that are created mathematically and do not represent actual features in the beam. If a large number of profiles are taken at many angles, these ridges and valleys cancel each other and their affect on the final reconstruction is negligible. However the limited number of slits, which can physically fit on the disk, prevents adequate cancellation of the ridges and valleys, resulting in the presence of some number of artifacts.

To mitigate the effects on the power distribution normalization, one of the filters available is a "hat" filter. This filter assumes that the beam power is distributed around the centroid as a "blob" and not radially like a starfish. It calculates the best fit ellipse for the region where the power density is equal to or greater than the peak power density multiplied by $1/e^2$. The ellipse is expanded by 25% and any pixel values outside the ellipse are zeroed. The beam power is distributed over the reconstruction after this filter is applied. If necessary, a smoothing filter may be applied in order to remove any remaining high frequency noise.

OPERATION OF EB_MkTomo.exe

Install EB_MkTomo.exe onto the computer to be used for data acquisition and/or computed tomography using the instructions listed in Appendix VII. A step-by-step description of the user input required to run the EB_MkTomo.exe program is given below. The instructions and descriptions of the various commands are divided into the same three steps or sections of the program described in Figure 10 in the previous section. These instructions follow the installation of both LabVIEW and EB_MkTomo.exe on the computer and the starting of both programs.

Step 1: IMPUT ELECTRON BEAM AND DATA ACQUISITION PARAMETERS*

Enter Parameters and Click Left Arrow to start the VI.

- ✓ Choose **Data Source** from the pull-down menu.
- ✓ Set data acquisition and filter parameters
- ✓ Choose reconstruction filters using the slide switches
- ✓ Start the VI by clicking the solid white left arrow Run button in the toolbar

When EBMkTomo.exe is opened, the user will see the window shown in Figure 11. The desired parameters for the beam reconstruction can be set up using the following instructions:

EBMkTomo.exe can be used to reconstruct data from either data files or a real time data acquisition. Before starting, the user should use the **Data Source** pull-down menu to select Data Acquisition or Data File.

If real time data acquisition is selected or the data file does not contain a standard header, the **Data Acquisition Parameters** controls must also be set by the user.

The **Sinogram Filter** controls need not be set at this time, as they may be adjusted in the next step. Two slide switches apply filters to the tomographic restruction, Apply Hat Filter

* Note: In the following directions the names of controls or indicators and the selections in pull-down menus are given in shaded Arial Narrow or **Arial Narrow Bold** font.

to Reconstruction and Smoothing Filter to Reconstruction, and should be set at this time, if desired. These filters reduce high frequency noise caused by the reconstruction process.

When the left arrow is clicked to start the VI, a sub-vi called EB2K_Sino_Data is opened. This sub-vi will automatically go into file or acquisition mode depending upon how the user set the Data Source pull-down menu.

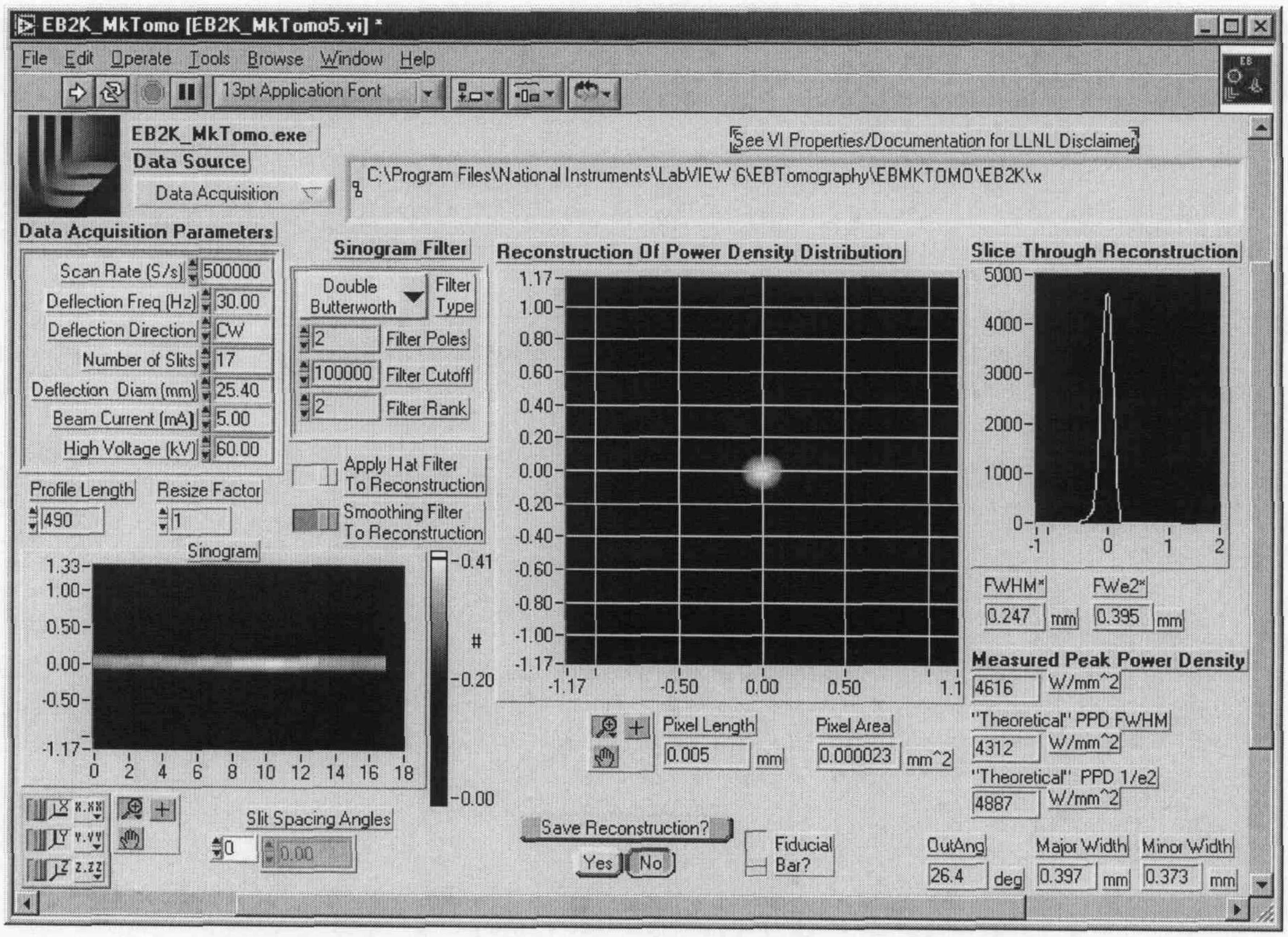


Figure 11. Main Virtual Instrument (VI) Front Panel of EB2K_Mktomo.exe

The following controls may be set before starting EB2K_MkTomo.exe.

Apply Hat Filter To Reconstruction: Enabling this slide switch (right) will apply a "Hat Filter" to reduce the effects of artifacts caused by the relatively low number of profiles used in the reconstruction.

Data Acquistion Parameters: These need not be set if the data is being read from a data file containing the standard header format agreed to by LLNL, KCP, and Y-12. If the data is coming from a data file without the header or if a data acquisition is being done, then the following parameters should be set in advance.

- ✓ Scan Rate (S/s): The sampling rate of the DAQ device used to acquire the data.
- ✓ Deflection Freq (Hz): The rate of the circular deflection of the beam.
- ✓ Deflection Direction: The direction, either CW or CCW, of the circular deflection.
- ✓ Number of Slits: The number of slits in the tungsten disk.
- ✓ Deflection Diam (mm): The diameter of the circular deflection of the beam.
- ✓ Beam Current (mA): The current of the electron beam.
- ✓ High Voltage (kV): The accelerating voltage of the electron beam

Profile Length: The user can select the maximum length (number of elements in the array) for the beam profiles used in the sinogram. The EB2K_MkTomo sub-vi also calculates a profile length based upon the scan rate, deflection frequency, and number of slits. The lower of the two length values is then used as the Profile Length in the sinogram.

Resize Factor: This allows the user to average points together to reduce the length of the profiles and thus speed up the reconstruction process. This averaging also acts as a smoothing filter on the data. Although a thorough study of the effect of applying this factor has not been done, it appears that it will lower the peak power density by a few percent. A Resize Factor other than 1 should only be used if the calculations are being done on an older computer and the processing time for the reconstruction must be shortened.

Sinogram Filter: See Description in **Step 2a.**

Slit Spacing Angles: One concept being considered for determining beam orientation uses slight variations in the angles between the slits. If a uniform slit disk is being used, the array should be left empty (default). If there is one wide angle followed by uniform angles then the wide angle may be put in the zero position with the rest left empty. Otherwise the angles between each of the slits may be entered into this array.

Smoothing Filter To Reconstruction: Enabling this slide switch (right) will apply a filter which removes high frequency noise from the reconstruction by doing a weighted average of each point with its nearest neighbor. The value of each point is multiplied by 4, the horizontal and vertical neighbors are multiplied by 2, the diagonal neighbors are multiplied by 1, and the sum of all of these is divided by 16.

Step 2: EB2K_Sino_Data OPENS TO READ IN DATA

A good sinogram is essential for an accurate reconstruction of the beam power density distribution. The purpose of this sub-vi is to allow the user to adjust parameters to ensure this type of accuracy. All of the calculations necessary for measurements, such as beam size and peak power density, are dependent upon accurate recording of the parameters used during beam acquisition. The user should make sure that the controls in **Data Acquisition Parameters** are correct and change them if necessary. The window which the user will see when opening the sub-vi is shown in Figure 12.

The tomographic reconstruction algorithm emphasizes high frequency data. It is therefore important that noisy data be filtered before being processed. The graph, Normalized Overlapping Peaks, displays all of the rows in the sinogram in consecutive order and allows the user to see the amount of noise on each. One of the filter options can then be used to reduce this noise. Filtering to improve the sinogram should be done even if the hat or smoothing filter was selected for the completed reconstruction.

The mode selected on the front panel of the main VI will automatically be transferred to this sub-vi when it opens. The Data File mode is described in Step 2a, and the Data Acquisition mode is described in Step 2b.

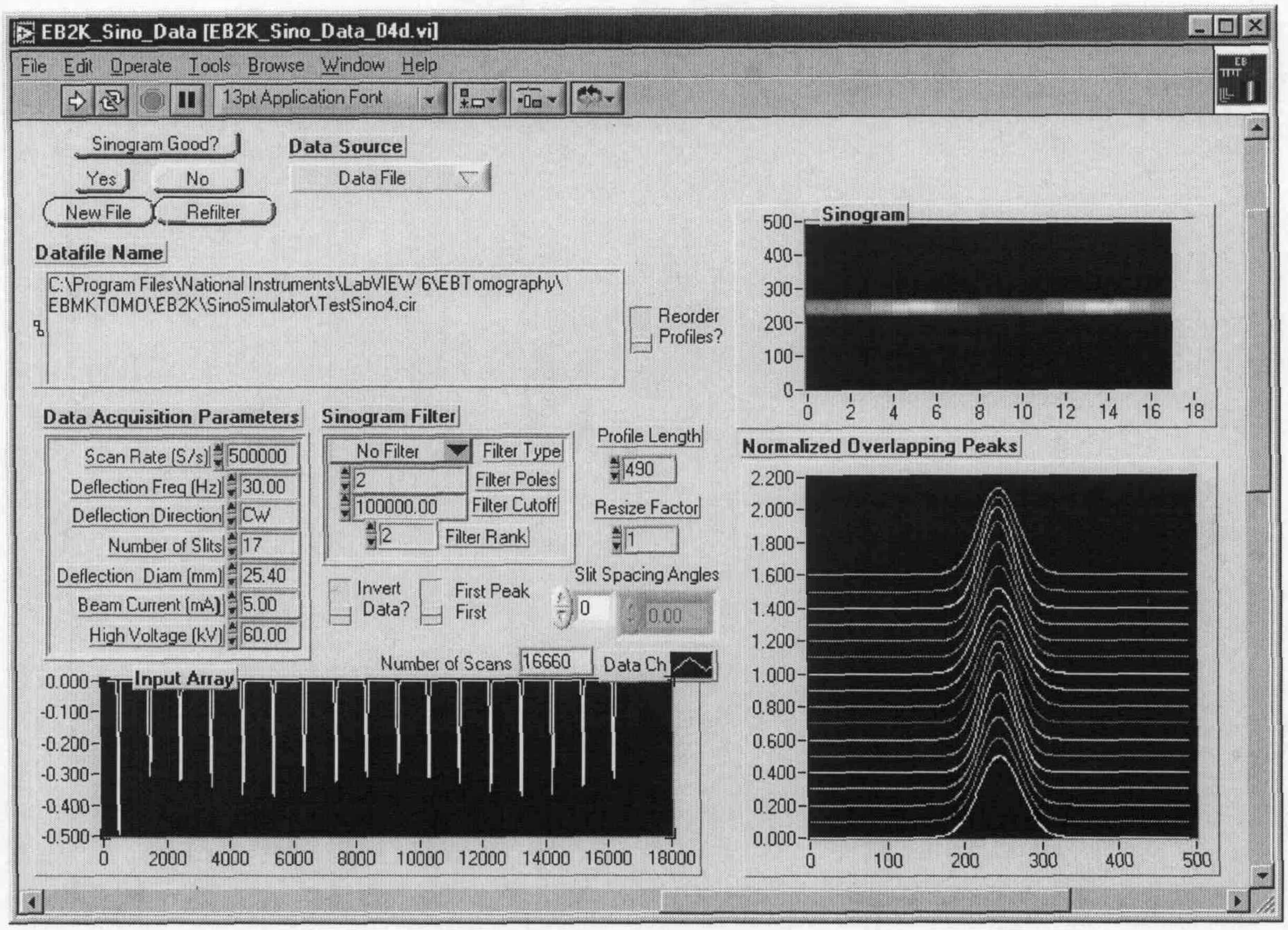


Figure 12. EB2K_SinoData window in Data File Mode

Step 2a: READ IN EXISTING DATA FILE FOR RECONSTRUCTION

Data File

- ✓ Choose the name of the data file in the Windows file selection dialogue box
- ✓ Examine the sinogram in the displays labeled **Sinogram** and **Normalized Overlapping Peaks**
- ✓ If necessary, click on **No** or **Refilter** and change parameters
- ✓ When satisfied with the sinogram click on **Yes** to return to EB_MkTomo.exe

If **Data File** is selected, the EB2K_Sino_Data sub-vi opens a Windows file selection dialogue box, and the user may choose the data file to be opened. The selected file and its path will be displayed in the **Datafile Name** indicator.

If a data acquisition is desired instead, click on Cancel, and then on Continue in the error dialogue box. Select Data Acquisition from the Data Source pull down menu and click on the New File button. The sub-vi will change to Data Acquisition mode.

Once the file is selected, Sinogram Good? flashes in the upper left corner. Below it are four control buttons:

Yes indicates the user is satisfied with the sinogram and will send the sinogram back to the main vi for reconstruction and closes the EB2K_Sino_Data window.

No indicates that a parameter, filter, or other control must be changed and puts the sub-vi into a wait mode that gives the user time to change the control settings after looking at the Input Array and the Sinogram. The flashing Sinogram Good? switches to a flashing Change Parameters, the Yes button is changed to Done, and the other three buttons are grayed out. Once the user has changed the other parameters and clicks on Done, the sub-vi completes the sinogram construction using the new data acquisition and filter parameters on the data as read from the file. The flashing Sinogram Good?, the Yes control return, and the other three buttons are reactivated. The user can then decide whether to send the new sinogram to the main vi or do further adjustments.

New File will reopen the file selection dialogue box.

Refilter will allow further filtering of the current sinogram. The action taken is similar to the No button except that the sinogram is constructed using the data as filtered in previous passes instead of the data as read from the data file.

The following parameter controls may be changed if No or Refilter are selected:

Data Acquisition Parameters: These are the same as seen in the cluster on the EB2K_MkTomo front panel.

Scan Rate (S/s): The sampling rate of the DAQ device used to acquire the data.

Deflection Freq (Hz): The rate of the circular deflection of the beam.

Deflection Direction: The direction, either clockwise (CW) or counter-clockwise (CCW), of the circular deflection.

Number of Slits: The number of slits in the tungsten disk.

Deflection Diam (mm): The diameter of the circular deflection of the beam.

Beam Current (mA): The current of the electron beam.

High Voltage (kV): The accelerating voltage of the electron beam

Reorder Profiles?: The profiles acquired in one circle around a slit disk must be reordered before being placed in the sinogram representing a scan of the beam through 180 degrees. If the data were originally acquired by EB2K_SinoData, then the reordering was done when the data was acquired. If the data acquisition was done by another program and this reordering was not done when the data was acquired, this slide switch must be activated.

Sinogram Filter: The user can select one of five filters or no filtering at all with three parameters that are used by the appropriate filters.

Filter Type: The user can choose from the following filter types.

- ✓ No Filter: Data is used as it comes from the file or data acquisition.
- ✓ Butterworth: A low pass Butterworth filter is applied with the number of poles determined by Filter Poles and the cutoff frequency determined by Filter Cutoff.
- ✓ Median: A median filter with a rank given by Filter Rank is applied to the data. For each element in the data array, a subset of the array centered about that element is found. The number of elements before and after the center element is determined by the rank. Each element is replaced by the median of its corresponding subset.
- ✓ Boxcar: For each element in the data array, a subset of the array centered about that element is found. The number of elements before and after the center element is determined by Filter Rank. Each element is replaced by the average of its corresponding subset.
- ✓ High Freq Cutoff: A Fast Fourier Transform (FFT) is applied to the data array, and all elements higher than the frequency given by Filter Cutoff are zeroed out. The inverse FFT is then applied.
- ✓ Double Butterworth: The lowpass Butterworth filter is applied twice - once in the forward direction and once in the reverse direction. This eliminates the frequency dependent phase shift of the Butterworth filter.

Filter Poles: The number of poles in the Butterworth and Double Butterworth filters.

Filter Cutoff: The low-pass cutoff frequency used in the Butterworth and Double Butterworth filters, or the threshold frequency in the High Freq Cutoff filter above which all elements in the FFT are zeroed out.

Filter Rank: The number of points before and after each element that make up the subset used by the Median and Boxcar filters.

Invert Data?: If the data is such that the peaks occur in the positive direction, then the data can be inverted to make them negative.

First Peak First: If selected then the first peak found in the data array will be used as the reference peak. Otherwise the peak with the greatest area under the curve is found.

Resize Factor: This allows the user to average points together to reduce the length of the profiles and thus speed up the reconstruction process. This averaging also acts as a smoothing filter on the data. Although a thorough study of the effect of using this has not been done, it appears that it will lower the peak power density by a few percent. A Resize Factor other than 1 should only be used if the calculations are being done on an older computer and the processing time for the reconstruction needs to be shortened.

Profile Length: The user can select the maximum length (number of elements in the array) for the beam profiles used in the sinogram. The sub-vi also calculates a profile length based upon the scan rate, deflection frequency, and number of slits. The lower of these two numbers is used to as the Profile Length in the sinogram.

Slit Spacing Angles: One concept being considered for determining beam orientation uses slight variations in the angles between the slits. If a uniform slit disk is being used, the array should be left empty (default). If there is one wide angle followed by uniform angles then the wide angle may be put in the zero position with the rest left empty. Otherwise the angles between each of the slits may be entered into this array.

The following indicators are used to display the data:

Input Array: This indicator displays the data used to construct the sinogram.

Normalized Overlapping Peaks: The normalized peaks of the sinogram are displayed in a single graph. A uniform offset in the vertical direction allows easy comparison of the height and width of the individual plots.

Sinogram: An intensity graph displays the sinogram.

Step 2b: TO ACQUIRE A NEW BEAM PROFILE

Data Acquisition

- ✓ Set the data acquisition parameters in **DAQ Device & Channel** and **DAQ Parameters**
- ✓ Examine the sinogram in the displays labeled **Sinogram** and **Normalized Overlapping Peaks**
- ✓ If necessary, click on No or Refilter and change parameters
- ✓ When satisfied with the sinogram click on Yes to return to EB_MkTomo.exe

When Data Acquisition is selected from the **Data Source** pull down menu then DAQ device controls and parameter cluster boxes will appear as shown in Figure 13.

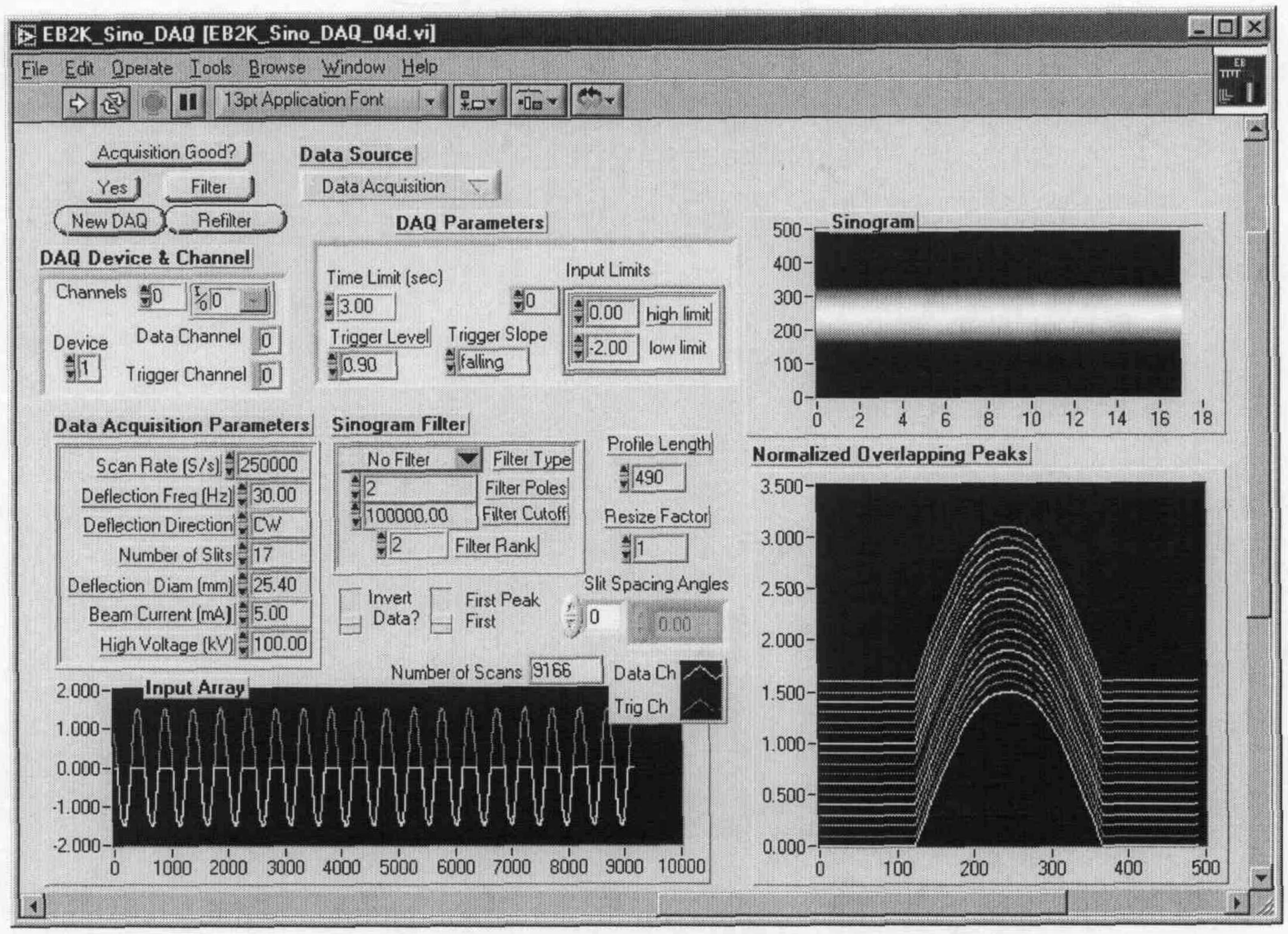


Figure 13. EB2K_Sino_DAQ window opened in Data Acquisition mode.

If a data file is to be used, select Data File from the **Data Source** pull down menu, and the sub-vi will switch modes and a file selection dialogue will open.

The **DAQ Device & Channel** box allows the user to enter the Device number selected in the MAX utility and channel numbers associated with the input numbers for that device (Channels). The user then sets the Data Channel and Trigger Channel to the appropriate Channels index. These numbers will normally be the same unless an auxiliary trigger source is used on a separate input channel. In that case, some DAQ devices may require that channel 0 be selected as the trigger channel.

In the **DAQ Parameters** box, the scan rate and number of scans will be set based upon the Scan Rate and Deflection Frequency set in the **Data Acquisition Parameters** box. The user can set the following values:

- ✓ The number of seconds the sub-vi will wait for a trigger before timing out (Time Limit (sec))
- ✓ Whether it triggers on a rising or falling edge (Trigger Slope)
- ✓ The level at which it triggers (Trigger Level)

- ✓ The input voltage range for each of the channels (Input Limits).

The DAQ device will set its internal gain to cover the range set by Input Limits. A negative value in the low limit control will set up the device for a bipolar measurement (unipolar measurements are positive only). The voltage seen across the current viewing resister will be negative so the device must be in bipolar mode. Set the lower limit to be below the most negative voltage expected, which is the voltage seen when the whole beam is sent through the center hold of the MFC. It is calculated by taking the negative of the product of the beam current and value of the beam current resister. The upper limit should be set to a positive value at a smaller absolute magnitude than the lower limit.

The **Data Acquisition Parameters**, **Sinogram Filter**, Invert Data?, First Peak First, Profile Length, Resize Factor, and Slit Spacing Angles controls and the **Input Array**, **Sinogram**, and **Normalized Overlapping Peaks** chart indicators will act as described in **Step 2a: Data File**.

Once an acquisition is made the Acquisition Good? indicator will flash in the upper left corner. Below it are four control buttons:

- ✓ Yes indicates the user is satisfied with the sinogram and will send the sinogram back to the main vi for reconstruction.
- ✓ Filter indicates that the filter controls must be changed and puts the sub-vi into a wait mode that gives the user time to change the filter settings before filtering the current input array. The flashing Sinogram Good? switches to a flashing Change Parameters, the Yes button is changed to Done, and the other three buttons are grayed out. Once the user has changed the filter parameters and clicks on Done, the sub-vi constructs the sinogram using the current input array and filter parameters. The flashing Sinogram Good? indicator and the Yes control return, and the other three buttons are reactivated. The user can then decide whether to send the new sinogram to the main vi or do further adjustments.
- ✓ New DAQ will start a new data acquisition.
- ✓ Refilter will allow further filtering of the current sinogram. The action taken is similar to the Filter button except that instead of constructing the sinogram from the **Input Array** data as read from the data acquisition, the constructs the sinogram using the data as filtered in previous passes.

Step 3: RECONSTRUCT THE DATA*

- ✓ Wait for the reconstruction to finish
- ✓ Save reconstruction in a file of tab delimited text if desired
- ✓ Program ends automatically
- ✓ Resultant reconstructed beam and measurements may be examined

When the Yes control is clicked in response to the flashing Sinogram Good? or Acquisition Good?, EB2K_Sino_Data automatically closes and the sinogram is sent to the main vi for processing. The number of elements in the reconstruction is the square of the length of the profiles in the sinogram, which is proportional to the time required to process a reconstruction. As an example, a 980 x 980 reconstruction takes 25 seconds on a 750 MHz Pentium III laptop computer, while a 512 x 512 reconstruction takes 8 seconds, and a 256 x 256 reconstruction takes 3.5 seconds. The resize factor can be used to reduce the profile size and thus speed up the calculation time. However, with the use of faster processors, the time required for reconstruction will not be an issue.

Some interpretation of the beam quality and focus can be done from the results displayed at the end of this step. The most obvious indication of the shape of the beam can be seen directly on the **Reconstruction of Power Density Distribution** intensity graph. The user can quickly see the shape of the beam and whether it is circular, elliptical, or some other shape. An ideal sharply focused beam will be a circular Gaussian beam, while an elliptical or other shape will indicate defocus or some other problem.

A comparison of the Major Width and Minor Width measurements can also show the degree of roundness of the beam. These two measurements will be very close when the beam is round, but will differ greatly as the beam gets more elliptical. The peak power densities can be used as an indication of how well the beam approximates a Gaussian shape as the **Measured Peak Power Density** should only vary from the "theoretical" values by a few percent if the beam is round and Gaussian shape. The Slice Through Reconstruction graph

* Note: Three example reconstructions are provided in the section that follows. Each example comes with a data file that can be used as to practice the reconstruction steps described below.

is a plot of a row going through the center of the reconstruction. This will show excessive noise in the reconstruction.

Once the sinogram is returned from EB2K_Sino_Data and the reconstruction starts, EB2K_MkTomo will ignore any changes to its front panel controls, which should have been set before starting the vi. The **Data Acquisition Parameters**, **Sinogram Filter**, Profile Length, and Resize Factor controls will be updated to reflect any changes made in EB2K_Sino_Data.

When the reconstruction finishes it will be displayed on the **Reconstruction of Power Density Distribution** intensity graph. The **Slice Through Reconstruction** graph will show a profile through the center of the reconstruction. This will give the user an indication of the amount of noise in the reconstruction. There are also indicators that provide information of the reconstructed beam power density:

> Pixel Length: The length in millimeters of one element in a sinogram profile and one side of a pixel in the **Reconstruction of Power Density Distribution** intensity graph. This is calculated from the scan rate, deflection frequency, deflection diameter, and resize factor.
>
> Pixel Area: The area of a pixel (mm^2) in the **Reconstruction of Power Density Distribution** intensity graph.
>
> FWHM*: The equivalent Full-Width Half Max (FWHM) is the diameter of a circle equivalent in area to the area of the reconstruction where the beam power density is equal to or greater than half of the maximum power density. This calculation of equivalent area is done because it is not possible to calculate a FWHM for non-circular beams.
>
> FWe2*: This is similar to FWHM* except the equivalent area is taken at a point where the beam power density is equal to or greater than the maximum power density multiplied by $1/e^2$.
>
> **Measured Peak Power Density**: The peak power density in the reconstruction.

"Theoretical" PPD FWHM*: The peak power density of an ideal Gaussian-shaped beam power density with a FWHM value equal to FWHM*.

"Theoretical" PPD FWe2*: The peak power density of an ideal Gaussian-shaped beam power density with a FWHM value equal to FWe2*.

Out Ang: The angle between the x-axis of the reconstruction and the major axis of an ellipse fit to the area of the density distribution at the FWe2* level.

Major Width: The width of the fitted ellipse along the major axis.

Minor Width: The width of the fitted ellipse along the minor axis.

When the reconstruction is finished, the user can save the data directly to a file. If a data acquisition is done, a Save Sinogram? indicator will flash in the bottom center of the panel. Clicking on Yes will open a dialog window for saving the sinogram with its header information, after which, the Save Reconstruction? indicator will flash at the bottom center of the window. If the user wishes to save the reconstruction, click on Yes, otherwise click on No. The Fiducial Bar? slide switch control will place twenty pixels equal to half of the peak power density value in the first row in the bottom left hand corner. This will help a user orient the data file if opened in an application that does not start with (0,0) in the lower left corner.

Once the user has finished choosing whether or not to save the files, EB2K_MkTomo will stop. The user may, at this point, print out the screen for a quick record of all of the beam and acquisition parameters and results.

EXAMPLE RECONSTRUCTIONS

Example 1: Idealized Circular Gaussian Beam – Test_CircularGaussian.dat*

This file contains a sinogram generated from a series of ideal Gaussian profiles. In the ideal case, this will reconstruct into a circular Gausian power density distribution. To construct the test file, a circular Gaussian beam with a width of 0.5 mm at the 1/e2 point is simulated. Profiles were taken at 17 equally spaced angles and a convolution simulated the effects of a 4 mil slit. Typical header information for a 60 kV, 5 mA beam is added.

To run the reconstruction, select the file in the Data File mode of EB2K_Sino_Data. No filtering is necessary, and symmetry eliminates the need to reorder the profiles. Results should match those shown in Figure 14.

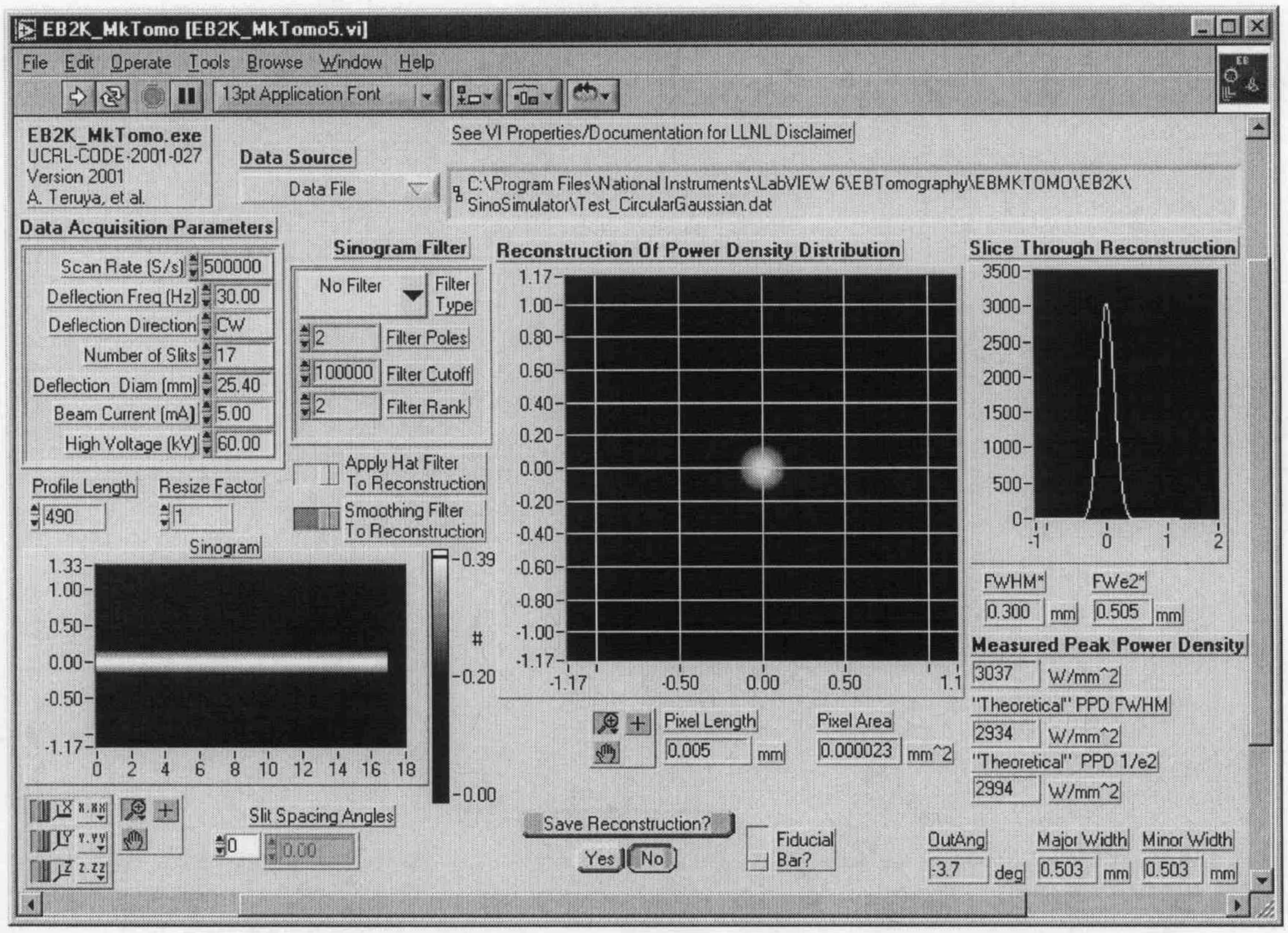


Figure 14. The window created when reconstructing the beam profile from the file, Test_CircularGaussian.dat, provided with the software package.

* This file is included on the CD which comes with the enhanced MFC device.

Example 2: Idealized Elliptical Gaussian Beam – Test_EllipticalGaussian.dat*

This file contains simulated data for an elliptical Gaussian beam, 0.8 mm width on the major axis and 0.4 mm width on the minor axis at the 1/e2 point. The major axis is 60 degrees above the positive-x axis (3:00). Profiles are taken at 17 equally spaced angles. Convolutions simulate the effects of a 5 mil wide slit at the 6:00 position and 3 mils for the other slits. Typical header information for a 60 kV, 5 mA beam is added.

To run the reconstruction, select the file **Test_EllipticalGaussian.dat** in the Data File mode of EB2K_Sino_Data. No filtering is necessary, but the profiles must be reordered. Results should match those shown in Figure 15.

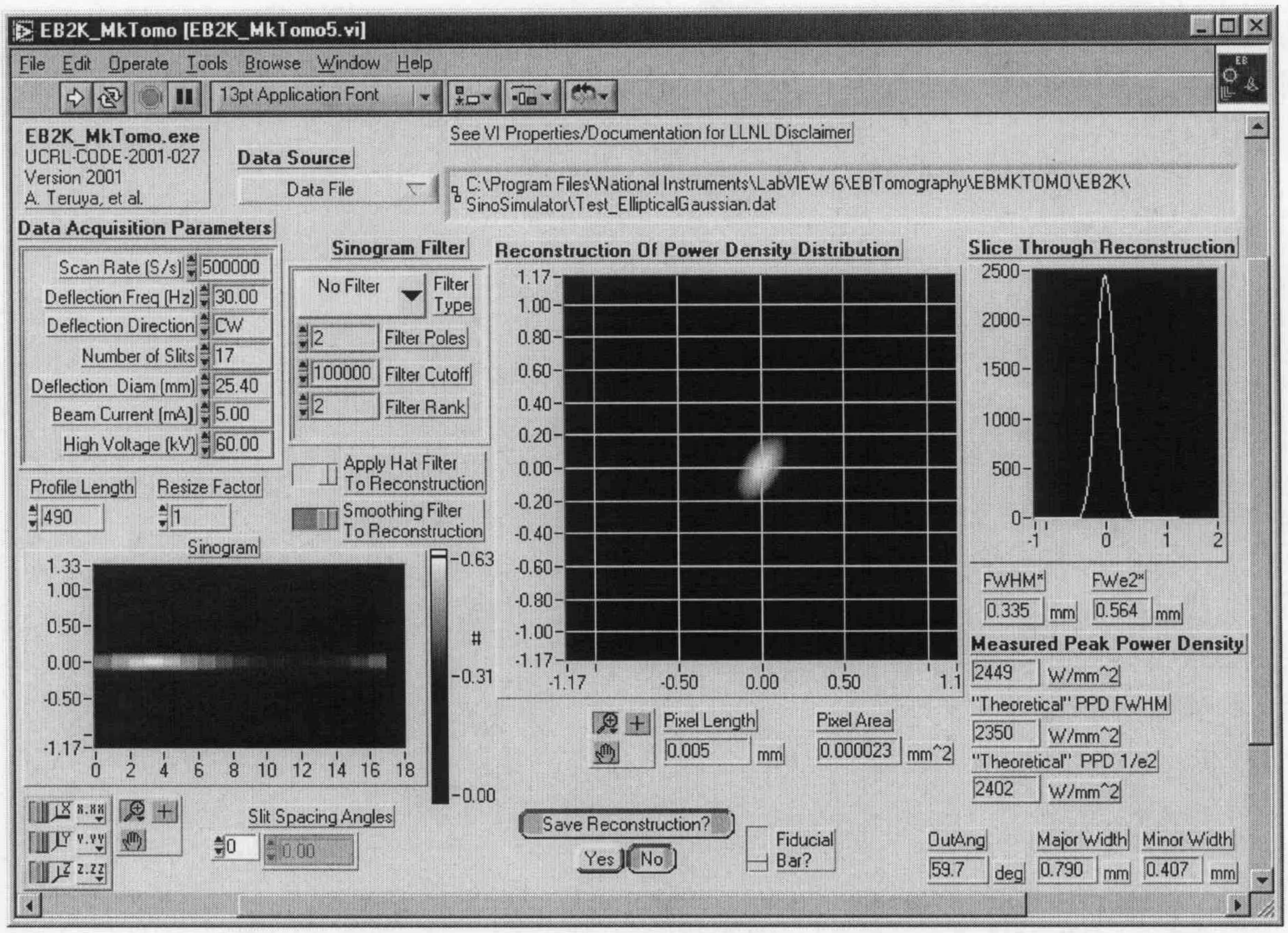


Figure 15. The window created when reconstructing the beam profile from the file, Test_EllipticalGaussian.dat, provided with the software package.

* This file is included on the CD which comes with the enhanced MFC device.

Example 3: Data from a 60kV, 5 mA Beam – Test_60kV5mA_Beam.dat*

This file contains data from a 60 kV, 5 mA beam taken on a Hamilton Standard electron beam welding machine (S/N 175) at Lawrence Livermore National Laboratory. The data were acquired using an enhanced MFC device manufactured as part of the same lot as those to be distributed throughout the DOE complex.

To run the reconstruction, select the file **Test_60kV5mA_Beam.dat** in the Data File mode of EB2K_Sino_Data. Filtering should be done to reduce noise. In this example, a Double Butterworth filter is applied to the sinogram, and a hat filter and smoothing filter are applied to the reconstruction. The sinogram does not need to be reordered. Results should match those shown in Figure 16.

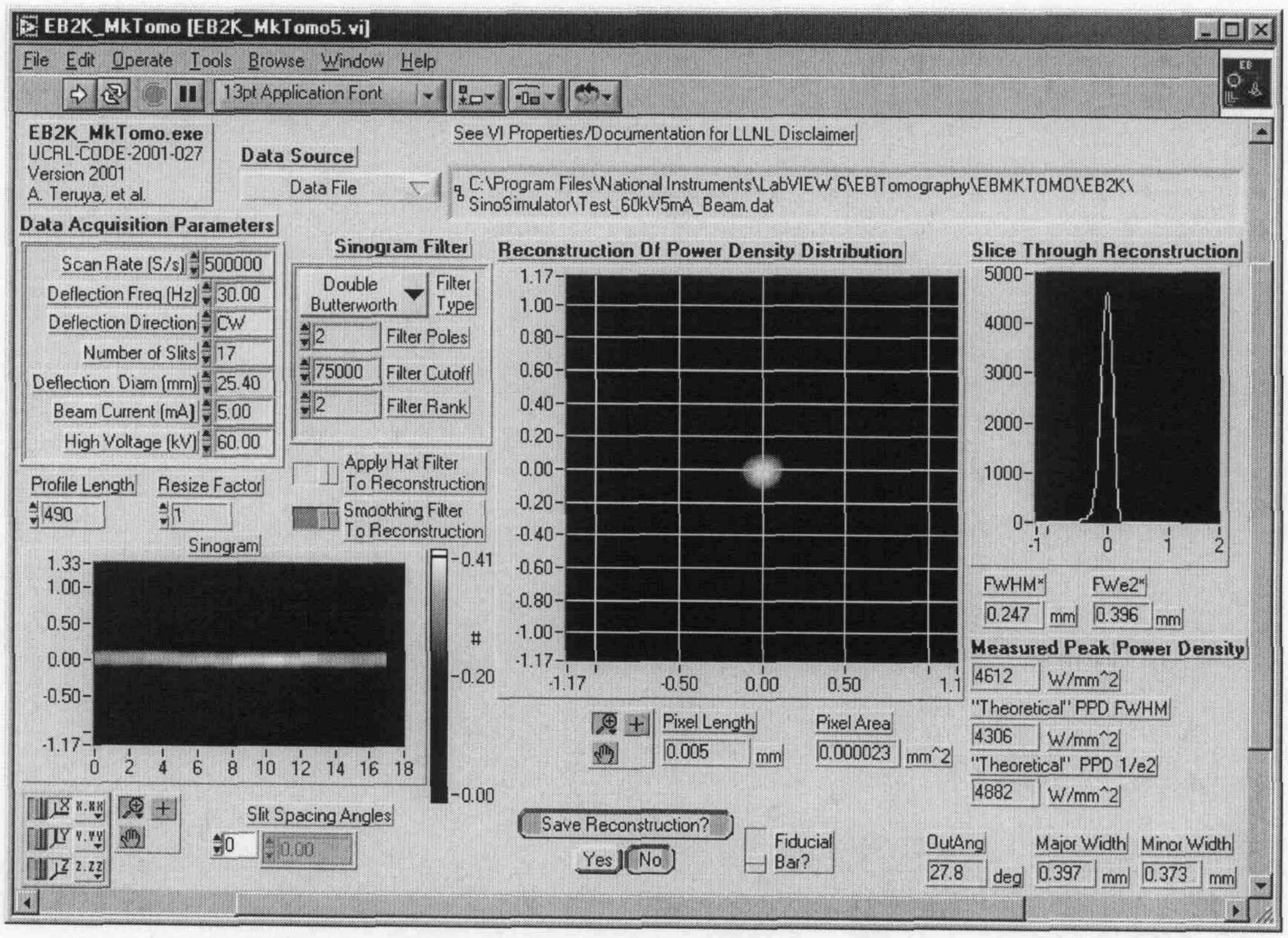


Figure 16. The window created when reconstructing the beam profile from the file, Test_60kV5mA_Beam.dat, provided with the software package.

* This file is included on the CD which comes with the enhanced MFC device.

SUMMARY

The MFC diagnostic enables weld operators to repeatedly produce a focused beam of a known power density, which is not currently possible with commercial electron beam welders. These electron beam diagnostics also provide weld engineers, for the first time, the ability to acquire a permanent quality control record of the beam, to repeat and duplicate welds on the same machine, and to transfer welding parameters between machines and facilities. The redesign of the MFC diagnostic hardware described in this manual improves the quality of the acquired data, and enables a more accurate computed tomographic reconstruction of the power density distribution of the electron beam to be performed than previously possible.

The MFC and its associated hardware and software described in this manual are undergoing an evolutionary process. Changes to both the software and hardware components of this system will be required as the users at LLNL, the Y-12 Plant, the Kansas City Plant, Sandia National Laboratory, and Los Alamos National Laboratory evaluate beam focusing and quality control issues in their environment and on their respective electron beam welding machines. It is our goal to help incorporate these new software and hardware changes into this system to allow easy transferability of data between the DOE facilities in the out years of this program. The users are therefore encouraged to contact LLNL with suggestions for improvements to the MFC beam profiling system. Please direct any comments and suggestions to:

MFC hardware and electron beam welder setup

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APPENDIX I: MASTER PARTS LIST FOR ENHANCED MFC ASSEMBLY

Table I.1. List of parts comprising each enhanced MFC Assembly.

Part Name	Sub-Assembly	Part Number	Quantity
Insulator Body	Insulator Cup	ICA-IB1-001	1
Insulator Base	Insulator Cup	ICA-IB2-002	1
Tungsten Slit Disk (Wide Slit)	Heat Sink	HSA-WWA-003	3
Flange Clamp	Heat Sink	HSA-FCA-004	1
Heat Sink Base 3 in.	Heat Sink	HSA-3BA-002	1
BNC Connector	Heat Sink	HSA-BNC-005	1
Heat Sink Body 3 in.	Heat Sink	HSA-3BY-001	1
Baseplate 3 in.	Heat Sink	HSA-3BP-006	1
Copper Slit Disk (Equal Angle)	Beam Trap	BTA-CSD-005	1
Beam Trap Body	Beam Trap	BTA-BTB-002	1
Faraday Cup	Beam Trap	BTA-3FC-001	1
Dowel	Beam Trap	BTA-SD1-006	1
Beam Stop	Beam Trap	BTA-3BS-003	1
Graphite Disk	Beam Trap	BTA-3BT-004	1
Miscellaneous Parts			
Socket Head Cap Screw, 4-40x3/4"	N/A	SHCS-440-0750	6
Socket Head Cap Screw, 4-40x3/8"	N/A	SHCS-440-0375	6
Socket Head Cap Screw, 4-40x1/4"	N/A	SHCS-440-0250	2
Hex Head Cup Pt. Set Screw, 4-40x1/4"	N/A	HHCS-440-0250	2
Hex Head Cup Pt. Set Screw, 4-40x 3/32"	N/A	HHCS-440-0094	1
Slotted Flat Head Screw, 2-56x.187"	N/A	SFHS-256-0187	1
Dowel Pin, .125"x.375"	N/A	DPAA-125-375	3
Dowel Pin, .0625"x.187"	N/A	DPAA-625-187	1
Base Plate Leveling Screws	N/A	BPLS-BP1-001	3

Table I.2. List of tools provided with each enhanced MFC for assembly and disassembly.

Part Name	**Sub-Assembly**	**Part Number**	**Quantity**
50, 100, 250, 500, and 1000 Ω Resistor Box	N/A	---	1
0.050" Hex-Head Wrench	N/A		1
3/32" Hex Head Wrench	N/A	---	1
Flat Head Screwdriver	N/A	---	1
1/2" Open-End Wrench	N/A	---	1
Precision Level	N/A	---	1

APPENDIX II: CERTIFICATION INFORMATION

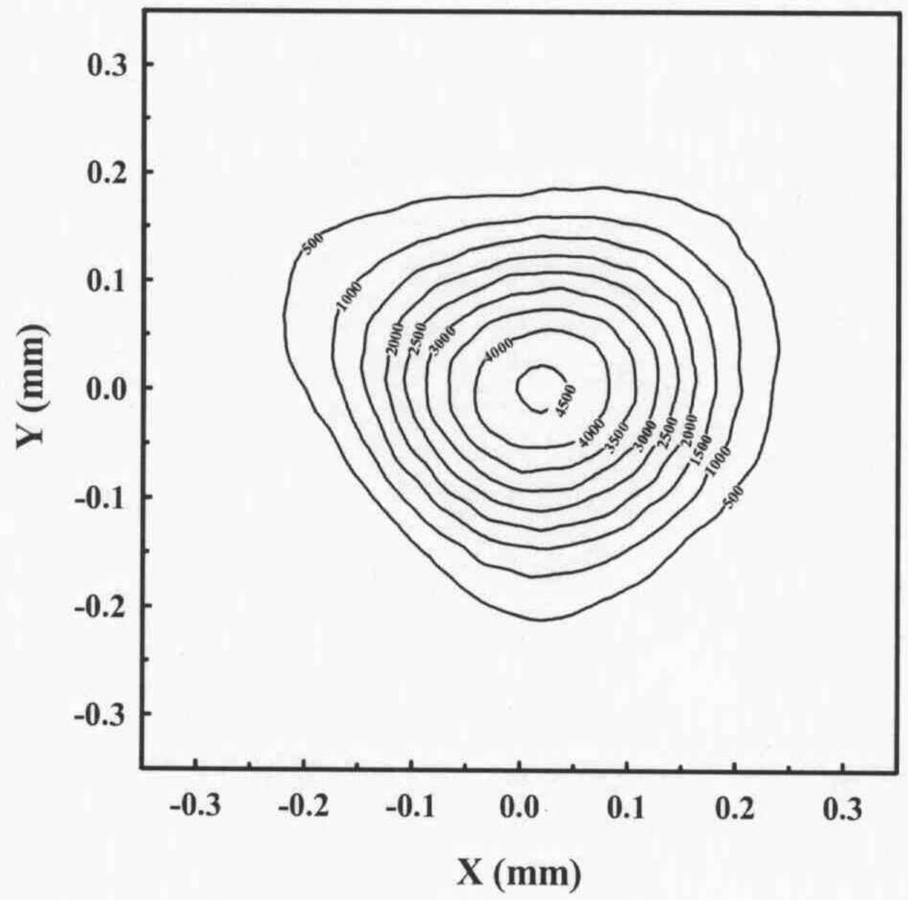
A series of tests were run on seven enhanced MFC diagnostic systems. Two of the systems (MFC-A-x) were manufactured as demonstration systems during 2001, and the remaining five systems (MFC-B-x) were recently manufactured and contain a number of modifications. These final five units are being delivered to selected locations in the DOE complex during FY'02.

Each diagnostic system was used to inspect a 5 mA, 60kV sharp focused beam on a Hamilton Standard electron beam welder (S/N 175) located at LLNL. The tungsten disk used to gather this data is of the same design shown in Appendix III. These data were taken using the same electron beam welding technician but not acquired on either the same day or during the same pumpdown. Each of the beams was reconstructed using the LLNL software, and the results are summarized in Table II.1. These results show the expected variation in peak power density and beam distribution parameters for the LLNL electron beam welder.

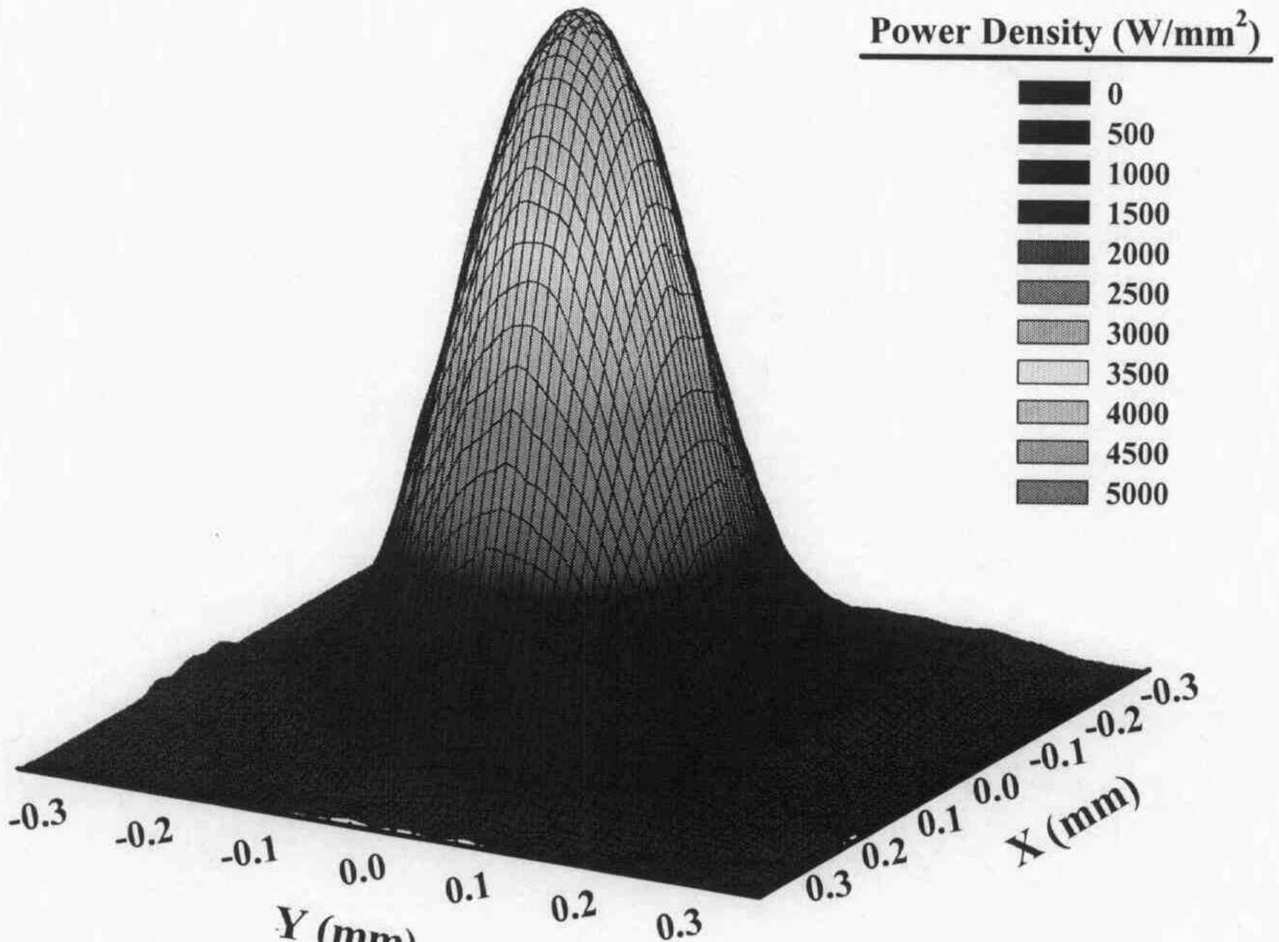
Table II.1. Summary of testing done at LLNL on seven enhanced MFC diagnostic systems.

Unit Number	**Peak Power Density (W/mm^2)**	**FWHM (mm)**	**FW1/e^2 (mm)**	**Major axis width (mm)**	**Minor axis width (mm)**
MFC-A-001	4358	0.244	0.431	0.431	0.364
MFC-A-002	4323	0.249	0.405	0.426	0.378
MFC-B-001	4625	0.239	0.389	0.417	0.364
MFC-B-002	4609	0.248	0.396	0.402	0.373
MFC-B-003	4622	0.243	0.391	0.421	0.354
MFC-B-004	4395	0.245	0.398	0.440	0.364
MFC-B-005	4591	0.244	0.392	0.417	0.350
Average	4503	0.245	0.400	0.422	0.363
Standard Deviation	137	0.0033	0.0146	0.012	0.010
Range	302	0.010	0.042	0.038	0.028

Figure II.1(a&b) show plots of the power density distribution of the electron beam in two different formats for one of the reconstructed beams (MFC-B-02) using a conventional Windows-based plotting/graphing program.



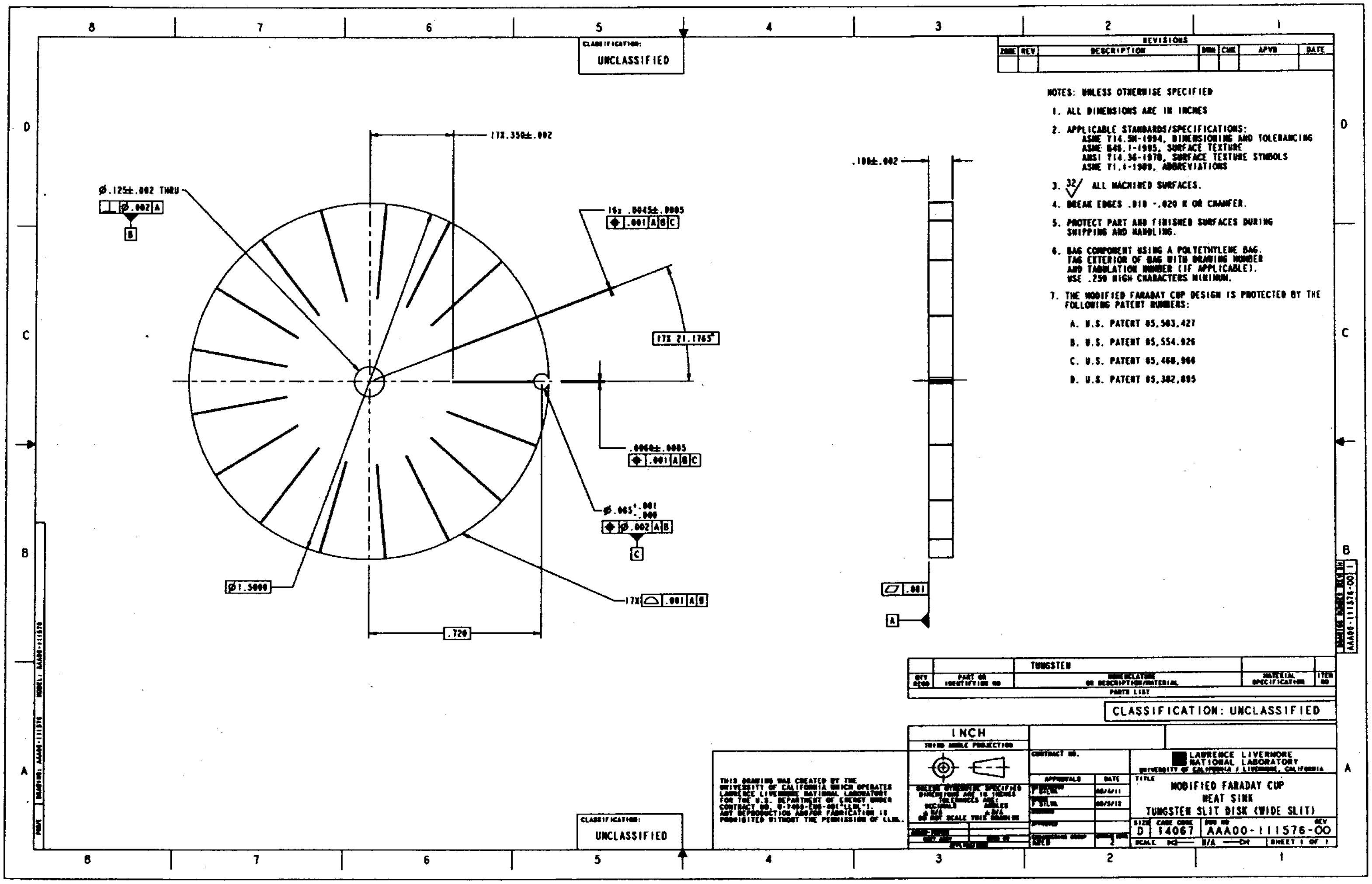
(a)



(b)

Figure II.1. Reconstructed electron beam (5mA, 60kV, sharp focus) from the data produced from MFC-B-002 on Hamilton Standard welder S/N 175. The top figure shows the power density distribution in contour format, while the lower figure shows this same data in 3-D format.

APPENDIX III: ENGINEERING DRAWING OF TUNGSTEN SLIT DISK



6/18/02, 5:02 PM

APPENDIX IV: BRAZING PROCEDURE FOR ATTACHING THE TANTALUM GROUNDING WIRE TO THE TUNGSTEN SLIT DISK

Materials Required:

1) Tantalum wire, 0.020 inch diameter, 3 inch long
2) Tungsten slit disk
3) Gold braze material, 0.002 inch thick foil, ~0.040 x~ 0.080 inch size
4) Titanium hydride
5) Acetone

Procedure:

1) Clean tungsten slit disk by gently sanding surface where braze is to be made to remove oxide. Then wipe tungsten disk and tantalum wire with acetone, and blow dry with nitrogen.
2) Spot weld tantalum wire to tungsten disk. The wire should be placed 180 deg from the wide slit, on the OD of the tungsten slit disk. The end of the wire should not extend more than 0.100 inch from the OD of the disk.
3) Apply a small amount of titanium hydride on the end of the wire and the tungsten disk where the braze is to be made.
4) Lay the gold braze foil on the tantalum wire.
5) Place in vacuum furnace with radiation heating elements. Evacuate to 10^{-6} torr
6) Heat furnace to 1050°C.
7) Soak at 1050°C for 5 minutes.
8) Heat through 1064°C to 1070°C.
9) Hold for 30 s after all of the braze alloy has melted.
10) Vacuum cool to room temperature and remove from furnace.

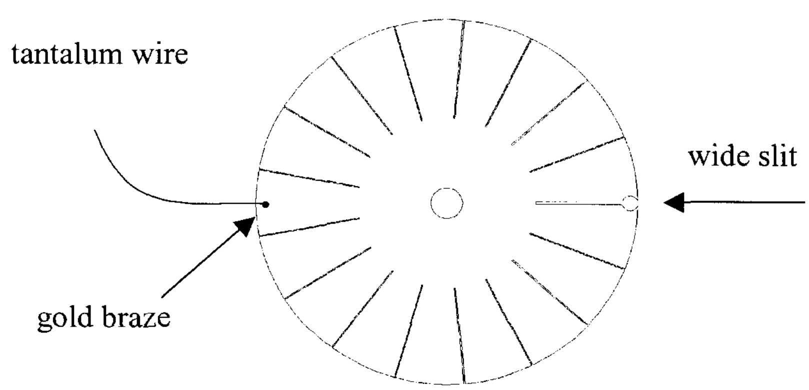


Figure IV.1. Schematic drawing of tungsten slit disk showing location of braze and tantalum wire.

APPENDIX V: FILE FORMATS

Standard Header Format

The Standard Header Format was the result of discussions between LLNL, Y-12, and KCP about what data about an MFC measurement should be kept for future reference. Information placed in the header in this format will be machine readable by data processing programs. It is expected that someday tracking of machine and component identification, part type and serial number, and beam parameters and power density measurements will be used in part certification records.

Each piece of information in the header is on its own line. An identifier is followed by an equals sign ("=") and the information. Appropriate units follow measurements. Additional comments may be placed in a comment section which has the identifier "Begin Comments" and ending with the character string "@$!".

Example Standard Header Format:

Plant ID = LLNL	[KCP, LANL, SNLL, Y-12, etc.]
Equip ID = 113484	
Captured Date = 01/23/02	[Date and Time of Original Acquisition]
Captured Time = 12:34	
Operator = Smith	
Part Number = 12345	[Part and Serial Nos. for use in certification records]
Serial Number = 6789	
High Voltage = 60.0 kV	
Beam Current = 4.00 mA	
Focus Current = 477.0 mA	
Filament Current = 37.70 Amps	
Filament Type = Ribbon	[Disk, Hairpin, or Ribbon]
Gun Type =	
Deflection Freq = 30.0 Hz	
Deflection Diameter = 25.4 mm	
Deflection Direction = CW	[CW or CCW]
Scan Rate = 500.0 kHz	[Sampling rate of data acquisition device]
Work Distance = 152.4 mm	[Distance from top of chamber to slit disk]
Vacuum Level = 10-6 to 10-3 Torr	[10^{-6} to 10^{-3}, 10^{-3} to 1, or 1 to 25 Torr]
Number of Slits = 17.0	
Trigger Slit Orientation = 6.0 O'Clock	[Clock position relative to operator]
Trigger Slit Width = 0.1143 mm	
Trigger Slit Type = Wide	
Effective Resistance Value = 0.0 Ohms	[Value of current viewing resistor]
Begin Comments:	
Additional information entered here. @$!	

Sinogram File Format

EB_MkTomo gives the user the option of saving a sinogram in a text file, if it is the result of a Data Acquisition or if the sinogram from a data file has a filter applied to it. The sinogram is saved with the header information needed to perform the tomographic reconstruction and beam power density calculation. The header information is in the standard data format. The data are stored in a tab-delimited format, where the number of columns is the number of slits and the number of rows is the number of elements in each profile.

Example header lines of a typical file:
High Voltage = 60.0 kV
Beam Current = 5.00 mA
Deflection Freq = 30.0 Hz
Deflection Diameter = 25.4 mm
Deflection Direction = CW
Scan Rate = 500.0 kHz
Number of Slits = 17.0
0.0007 0.0005 0.0003 0.0006 0.0011 0.0009 . . . (17 Columns Total)
0.0008 0.0008 0.0001 0.0006 0.0011 0.0010 . . .

Beam Reconstruction Format

EB_MkTomo gives the user the ability to save a reconstruction in a text file that can be read by other programs. It is saved in a three column tab-delimited format, where the first column is the x-dimension of each point (mm), the second column is the y-dimension, and the third column is the power density at that point (Watt/mm^2). The first line in the file has the three headings, also tab-delimited.

Example first four lines of a typical file:

x (mm)	y(mm)	Power Density (W/mm^2)
-1.168220	-1.168220	1.22460E+3
-1.168220	-1.163432	0.00000E+0
-1.168220	-1.158645	0.00000E+0

APPENDIX VI: GLOSSARY OF TERMS

- **BNC**: A type of coaxial cable connector. Short for British Naval Connector or Bayonet Nut Connector.
- **Computed Tomography**: A technique for determining the internal structure of an object based upon a number of scans taken at equally spaced angles around the object.
- **CT**: Computed Tomography
- **Current Density Distribution**: Expressed in mA/mm^2 for every point in the beam, it shows how the beam's total current is distributed around the area of the beam.
- **DAQ**: Data Acquisition
- **EB**: Electron Beam
- **Faraday Cup**: A device used to capture an electron beam. In its simplest form a Faraday cup is a cavity in a block of conductive material with a hole through which the beam enters. The beam and any backscattered electrons are captured when they hit the wall of the material and the current flows to ground through a cable and current viewing resister.
- **Filtered Backprojection**: A computed tomography technique that uses a filter in the frequency domain to process the scans used to reconstruct an objects structure.
- **LabVIEW**: A graphical programming environment from National Instruments, Austin, TX.
- **MAX**: National Instrument's Measurement Automation Explorer data acquisition configuration utility
- **MFC**: Modified Faraday Cup
- **Modified Faraday Cup**: A Faraday cup with a grounded slit placed above it. As a beam is swept across the slit only the fraction of the beam passing through the slit is captured.
- **National Instruments**: Manufacturer of LabVIEW and numerous data acquisition devices.
- **PC**: Personal Computer
- **Peak Power Density**: The highest power density in the beam in $Watts/mm^2$. The greatest penetration into the material will occur here.
- **Power Density Distribution**: Expressed in $Watts/mm^2$ for every point in the beam, it is calculated by multiplying the current density distribution by the accelerating voltage.
- **Sinogram**: A two-dimensional image used to display the scan data to be used in the tomographic reconstruction.
- **Sub-VI**: A VI called by a higher level VI. These are similar to subroutines, functions, or procedures found in other programming languages.
- **UNIX**: A type of operating system
- **VI**: Virtual Instrument
- **Virtual Instrument**: A program in the LabVIEW programming environment. It gets its name from the concept that a computer with data acquisition devices can be programmed to act as laboratory benchtop instruments such as oscilloscopes, chart recorders, meters, etc.
- **Zener diode**: A diode that can act as a voltage limiting device by breaking down when its reverse bias exceeds a certain voltage.

APPENDIX VII: SOFTWARE INSTALLATION INSTRUCTIONS

CD contents:

MFC_Handbook.pdf – This handbook.

Readme.txt - Any last minute comments.

Install_wLV - This directory contains the installer for computers that have LabVIEW already installed.

Install_woLV - This directory contains the installer for computers that do not have a copy of LabVIEW installed.

Installation Instructions

Open the directory containing the version of installer to be used based upon whether or not a copy of LabVIEW 6i or later is on your computer.

Click on Setup.exe to run the installer.

A dialogue will give you the option of selecting the directory in which the executable MakeTomo.exe will be installed. The default is c:\Program Files\National Instruments\LabVIEW\MakeTomo.

If you are using the version for computers without LabVIEW (in folder *Install_woLV*), the LabVIEW 6.0 Run-Time Engine Installation Wizard will automatically run. The Run-Time Engine will make it possible to run the MakeTomo.exe compiled program. It is not necessary if LabVIEW is already installed on the computer.