Tiny Particles, Huge Effects

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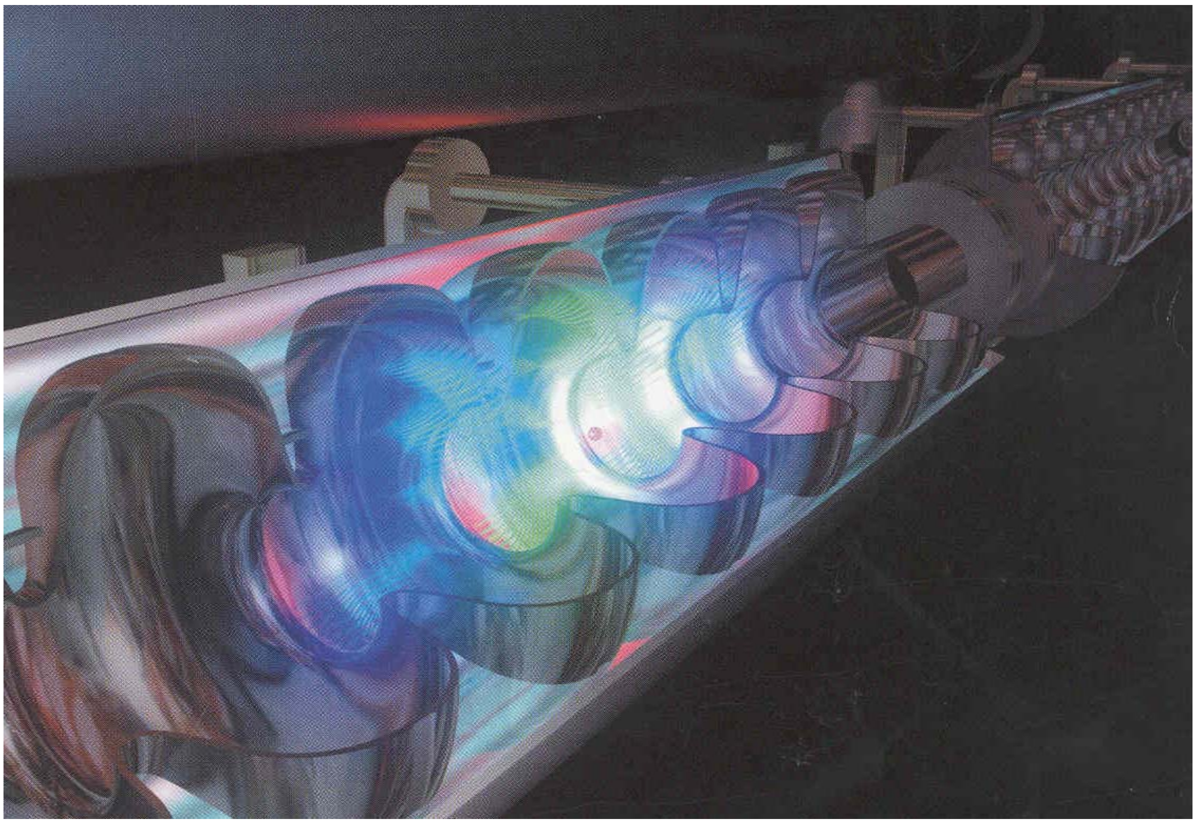


Abstract: In the realm of physics there is no such thing as useless data just like in the realm of psychology there is no such thing as wasted experience. Technical data along with emotional experience may have unexpected events, different interpretations, and/or varying impacts. However, just because a data set or an experience is presented differently, it does not make the data or experience less significant. With this being said, the following paper will deviate from the normal style of a technical paper in hopes of capturing not only the physical data, but in addition the whole Fermilab emotional experience.

Introduction:

Great things really do come in small packages. "Fifteen billion years ago, the entirety of our universe was compressed into the confines of an atomic nucleus." The worldwide web, which enables large worldwide collaborations, was invented at a particle physics laboratory. Electrons with a mass of ~9.1 x10^{-31} kg are able to attain 250,000,000,000 electron-volts of energy or 5 million times more energy than a television set!

Electron accelerators are by far the most common. A common home with a TV or computer monitor has in it a roughly 50,000 V electron accelerator. Accelerated electrons are also used by doctors and dentists to produce X-rays for diagnosis and gamma rays for treatment of illnesses. Because electrons do not weigh very much, they readily give off light when bent and it is this property that is exploited to produce medical X-rays and gamma rays.

In a way similar to how protons can collide with their antiparticles (called antiprotons) and transfer some of their energy to new states of matter via Einstein's E=mc^2, electrons can also collide with their antiparticles (called positrons). Electrons have the advantage of being able to transfer all of their energy to new matter while protons, which are made up of other particles called quarks and gluons, typically can only transfer about 10%. However, electrons have a disadvantage in that they radiate light. While useful as a source of X-rays as described above, this makes it difficult to accelerate electrons to the highest energy while using the "traditional" circular accelerator. It has been proposed that the next electron-positron collider use two linear accelerators.

Fermi National Accelerator Laboratory (FNAL) and the Northern Illinois Center for Accelerator and Detector Physics (NICADD) are dedicated to the research and development of new particle accelerator and detector technologies. The Fermilab NICADD Photoinjector Laboratory (FNPL), located at Fermilab, provides an opportunity for fundamental research into electron generation and beam dynamics. These research advances will help ensure the vitality and future of particle physics.

Who cares about particle physics? It is very difficult to care about something that is too tiny to see, much less understand. Can something so small really be of much importance and deserving of time to be studied?

Most people could care less about what happens in the microscopic realm. However, most people have experienced a time when they felt small, tiny, and even insignificant. Some hurtful incidents could be when your boss did not remember your name or when your mother forgot to pick you up from school. Or perhaps when you were an intern and felt like everything you did was of little importance and contributed to almost nothing.

Eddy the Electron, with a mass of only ~9.1 x10^{-31} kg, knows exactly how insignificant an intern feels. However, hope was not lost thanks to teachers, researchers, mentors, and physicists who care enough to give electrons and interns a time of day.

This paper will attempt to step inside the shoes of an electron in order to learn more about his/her life at A0 Photoinjector Laboratory. The approach of this attempt will be to tour through the main components of the FNAL A0 Photoinjector accelerator (see figure 1). A little Texan intern will join the tour and reveal her sympathy towards the tiny electron particle. Finally, the paper will conclude with a brief analysis of the electron/intern experience at Fermilab.

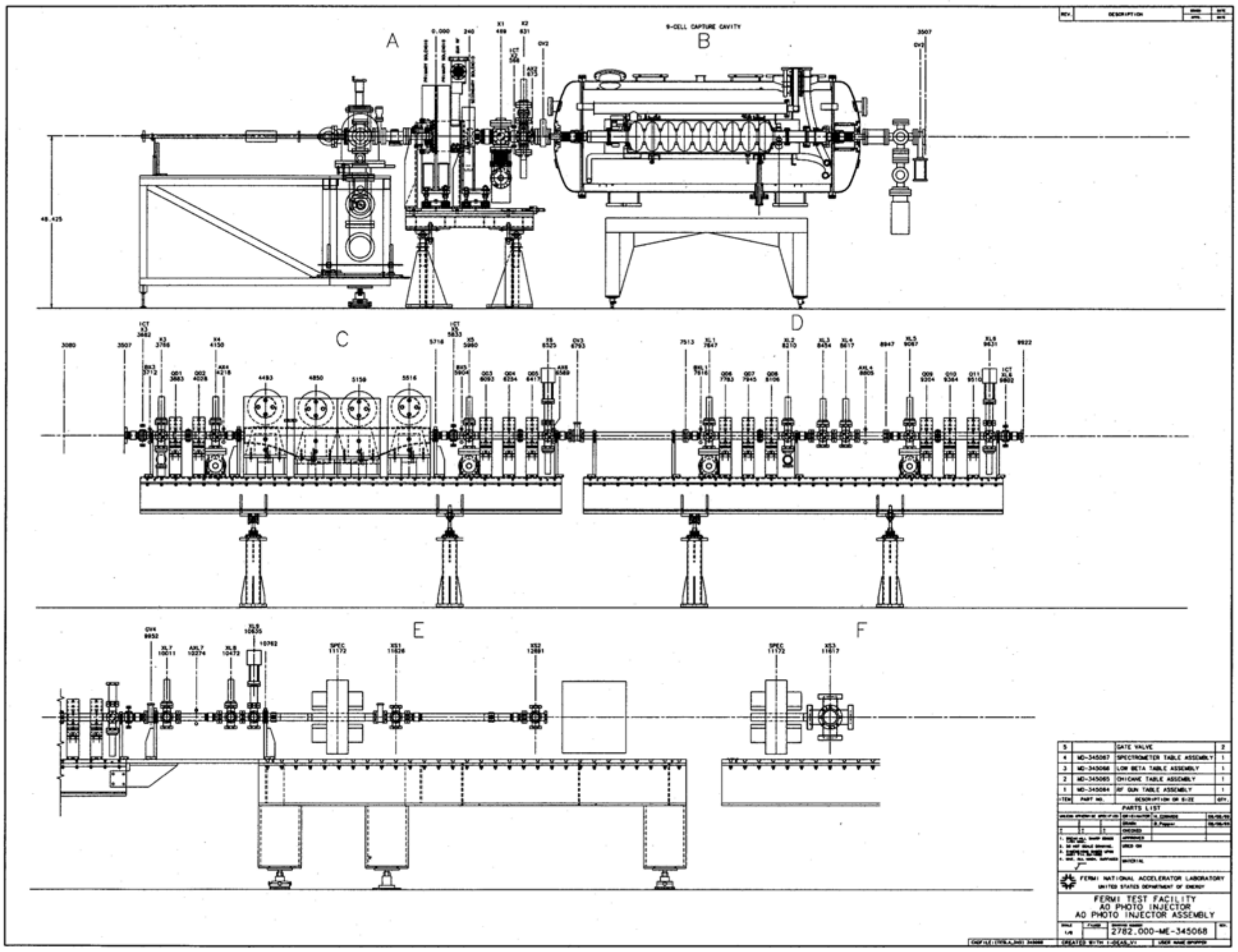


Figure 1. The principle components of the accelerator are: A.) the laser and photo-cathode source; B.) a nine-cell super-conducting RF cavity; C.) a chicane for beam compression. Some other components are: solenoids; dipole and quadrupole magnets; D.) cameras and diagnostic instruments; E.-F.) a spectrometer, Faraday cup, and dump.

--Eddy the Electron is created--

Eddy the Electron comes to life via an electron gun, which produces a cloud of electrons. There is a high DC potential between this gun and a plate so the electrons are drawn from the electron gun and accelerate towards the plate. Therefore, to accelerate charged particles a radio frequency (RF) system is really not a necessity. However, a sinusoidal radio frequency system is used for acceleration in order to produce a sinusoidal varying electric field that will create a resonating cavity. This resonating cavity is a perfect, clear home for Eddy the Electron because the cavity will resonate at a specific design frequency and any noise or other frequencies will not resonate in the cavity. The electron gun or cathode is placed in a device called a klystron seen in figure 2, which is used to amplify the RF.

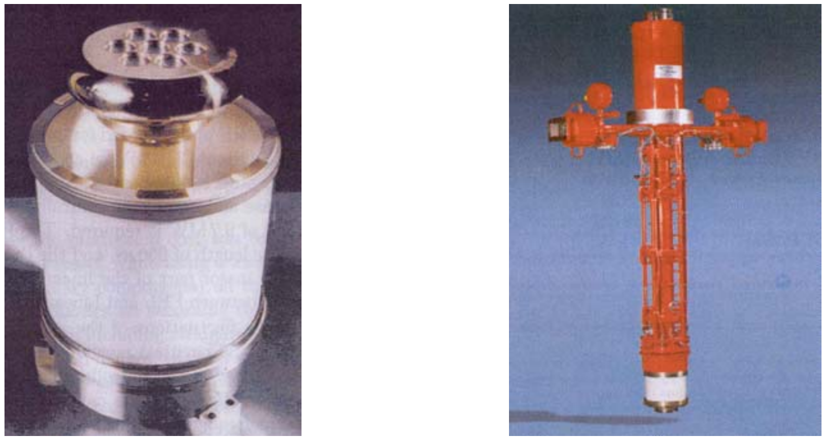


Figure 2. Left: Cathode of the multi-beam klystron.
Right: The Thomson TH1801 multi-beam klystron.

The ultimate goal of Eddy the electron is to gain enough energy to amplify the RF that needs to communicate with the electrons inside the cave where the accelerator lies. In order for this goal to be accomplished, a transportation medium with small losses is necessary i.e. the voice of the RF needs to be heard (resonate) like that of a drill sergeant. A coaxial cable works well to transfer waves at low frequencies. However, the RF waves are at high frequencies of 0.9-1.4 GHz so waveguides are used instead (see figure 3).

Figure 3. Thomsom 3MW Klystron with waveguide attached.

--Eddy the RF Electron hears about Elly the accelerated electron--

Eddy, along with his many other electron companions, can hear through the grapevine i.e. waveguide, which leads into the A0 south cave. The waveguide enters a cathode gun cavity where some electrons are lined up on one side (the cathode) while facing their counterparts, particles with opposite charges, on the other side (the anode). They are all connected across a voltage potential. This voltage potential creates electric field lines from positive (anode) to negative (cathode) charges.

Eddy is informed about a gap in the anode side and across from the gap, on the cathode side, were a special group of electrons. These specific electrons, as Eddy learned, were ready to be "accelerated." One particular electron caught Eddy's attention. She was intelligent, prepared, and patient. Yet Eddy hears from the waveguide that Elly is hesitant and lacks confidence. Eddy, however, feels that Elly has the potential to be accelerated, but he also knows that she will need some help.

Eddy, being an RF electron, was well aware that he could assist Elly in her acceleration in an indirect way. The radio frequency (RF) waves that Eddy amplifies accelerate electrons that are in an electric field in the direction opposite to the direction of the electric field lines (lines point from positive to negative). Therefore, the more energy that Eddy works for, the larger the amplification of the RF voice. This louder voice can in return, encourage Elly and the other electrons to a greater extent.

However, an encouraging voice can only do so much. The RF can easily accelerate Elly only after she takes that initial step from the cathode wall. Eddy knew that the first step was a big step for Elly and that she would need an extra pull from the cathode wall, which required more energy than he could provide.

--Eddy the RF Electron gets help--

Eddy sets his pride aside in order to help out Elly in her destiny to accelerate. Eddy thinks of his buddies, the photons, and remembers how much energy they tend to have. Eddy knows very well that his friends, the photons, although different than electrons, have the capacity to give an initial tug for Elly and are willing to provide a helping hand in the name of science.

The photons are made possible by a class-four laser room, which is, in itself, quite complicated. There are many components to keep track of and consequently, many places where the laser can err (see figure 4). Problems with various power supplies (e.g. the oscillator power supply) are somewhat common. The main goal of the laser is to convert infrared light waves into higher frequency ultraviolet light waves with the same RF frequency as the klystron/RF system previously mentioned.

In order for the photons to be able to help out Eddy and the other electrons, they need to have lots of energy. The energy for a photon is $E = f * h$, where f = frequency (1/second) and h = Planck's constant ($6.626*10^{-34}$ Joule-second). With this equation it can be noted that the higher the frequency is, the higher the energy becomes, which is why UV is used. However, the laser room efficiency of converting infrared to ultraviolet light is only ~20%. This low efficiency is mainly due to the complexity of the lattice structure of the doubling crystal that is used for changing frequencies (or wavelengths) of the laser beam.

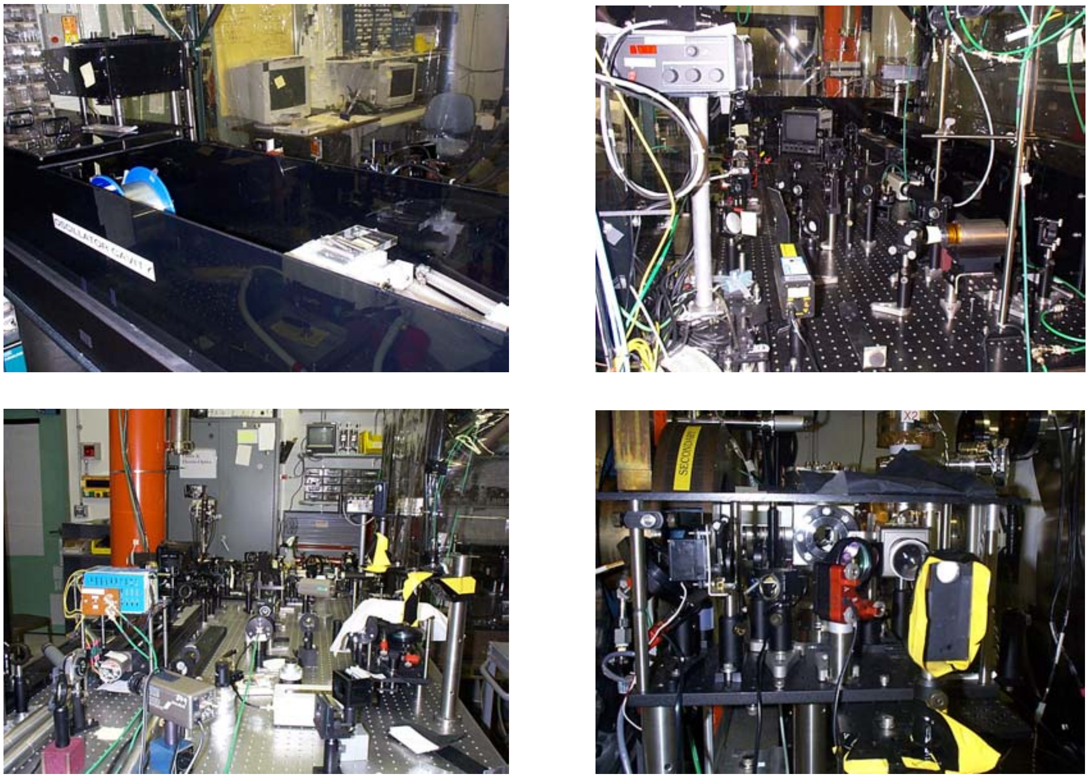


Figure 4. Top left: Oscillator cavity where the laser beam is created. Top right: Multi-pass setup where the amplitude (i.e. energy) of the laser is increased. Bottom left: Section where infrared light waves are converted to ultraviolet light waves and the resulting UV beam is transferred via the orange pipe in the far left. Bottom right: Laser optics setup in the beam line (remote-control iris is on the left).

--Elly the electron accelerates--

Elly experiences actual acceleration in a 1.5 cell cavity i.e. cathode gun. A0's one and a half cell cavity is comprised of a cavity with two cells, i.e. compartments, one cell being half the size of the other cell (see figure 5). The waveguide is attached to the second cell (the full cell), but Eddy the RF electron and his companions fill up both cells almost simultaneously. Neighboring cells are 180 degrees out of phase which causes the neighboring electric fields produced by the RF to be opposite in direction. This setup is known as "π mode acceleration" due to the 180° phase difference of the electric fields.

On the cathode wall the electric field is at a maximum. The laser beam's photons hit the cathode and eject electrons, including Elly, at this electric field maximum. The electric field returns to zero when the electrons reach the end of the half-cell. Timing of the photons from the laser with the phase of the RF is pertinent here because the electric field has to be in the correct direction as the electrons enter the neighboring one full cell. The electric field should be in the opposite direction of the electron's path in order to accelerate the electron forward and not backward. The electric field reaches another maximum when Elly and her group of electrons pass the center of the full cell. The electric field energy returns to zero when Elly leaves the 1.5 cell gun.

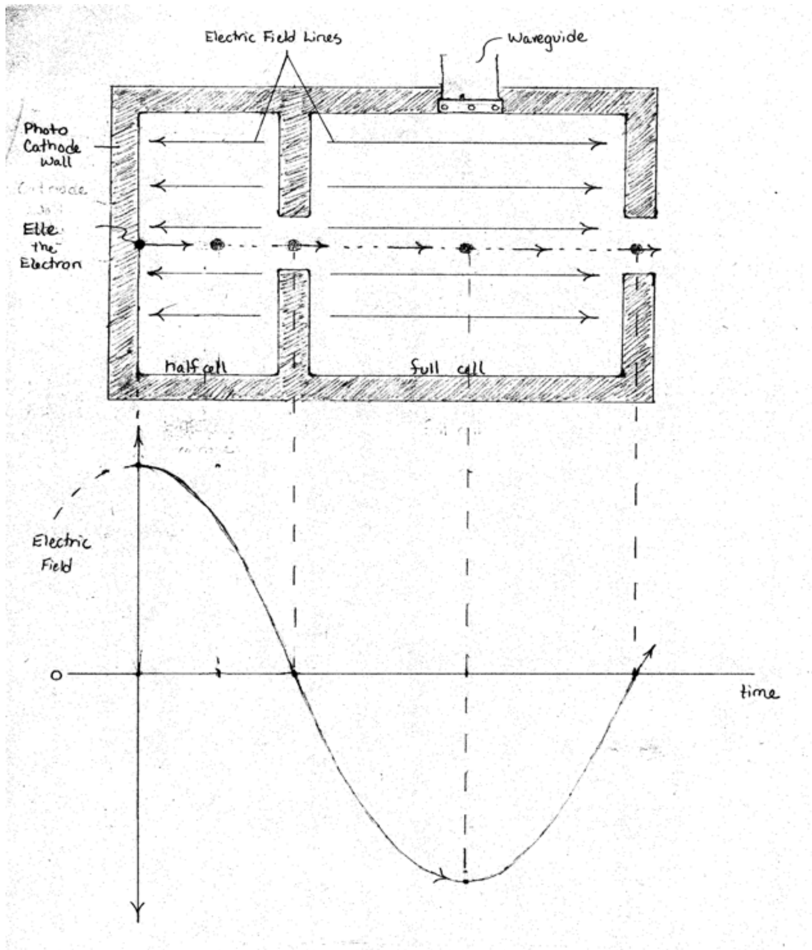


Figure 5. Gun at A0 Photoinjector Lab is a 1.5 cell/cavity gun.
Top: Schematic of 1.5 cell cavity.
Bottom: Corresponding graph of the electric field energy.

--Elly has no time to think--

Everything happens relatively fast for Elly the Electron. The klystron fires RF once every second (i.e. @ 1 Hz) and the laser fires a pulse of UV once every second. The klystron pulse lasts 30 microseconds with the electric field oscillating at a frequency of ~1.4 GHz (i.e. a period of ~0.7 nanoseconds). The laser pulse train is encompassed by the RF/Klystron pulse envelope, as seen in figure 6, and is therefore shorter in time (10 microseconds). The klystron /RF is longer because after the RF is triggered it needs some time to fill up both cells in the 1.5 cavity before the laser is triggered; some time is also allotted to the RF after the laser pulse. Although each laser pulse is very short, the electric field oscillations are very fast inside the RF envelope thereby allowing the electric field to capture the laser pulses.

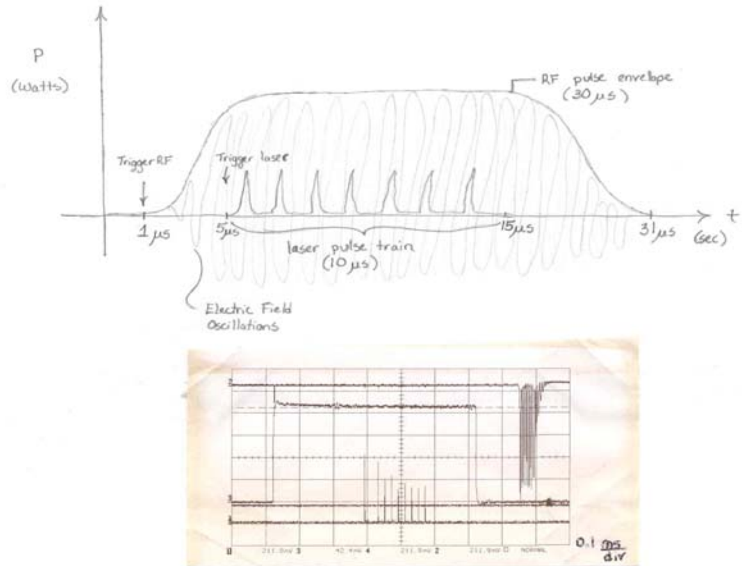


Figure 6. Top: Graph of power vs. time showing pulse event comparisons between the RF, the laser, and the electric field when the A0 Photoinjector gun is running. Bottom: actual printout from oscilloscope.

Elly the Electron can hardly believe her twist of fate. In a fraction of a second, she went from being a non-accelerating boring electron on the cathode to a highly accelerated electron with an energy of ~4 MeV. Elly, without knowing it, had the potential to be accelerated all along. She just needed an initial pull from the cathode to get her going. Elly was upset that she had no time to even think of giving thanks to her friends Eddy and the photons. She decided that she would thank them by being the best accelerated electron that she could be.

--The intern's perspective--

The RF system (i.e. the klystron), the waveguide, the 1.5 cell cavity, and the class four laser are all components that comprise the A-Zero Photoinjector/Cathode gun. Eddy the RF electron provides for RF amplification via acceleration energy; the waveguide provides a mean for RF communication to the electron beam with minimal power losses; the 1.5 cell provides a cavity along the beam line within the cave for the RF electric field to interact with the Elly and her group of electrons on the cathode wall; and the photons from the class four laser provide energy to pull off the electrons for acceleration.

The intern steps back, takes in everything that has happened to Elly the electron so far, and observes some striking similarities. The intern attends a university in Texas where she is preparing for the future. However she, like Elly, lacks self-confidence and does not see the potential that other people claim that she has. The intern, nonetheless, keeps working hard and one day she is chosen to be "accelerated" at a place called Fermilab. Here she is thrown in with people from all over the world, with different backgrounds and talents, who are kind enough to give her an initial tug and to help her accelerate.

One of the intern's projects in these early stages of acceleration was to improve a prototype of a remote-control iris. This iris is placed in a condensed space with other optics next to the Photo-cathode gun along the beam line. For this reason the intern had to design a prototype that was more compact yet still workable. The purpose of this automatic iris is to control, from outside of the main beam line cave, how much of the laser beam photons are injected into the cathode cavity where Elly is accelerated.

--Elly the Electron's check up--

There are several instruments, such as cameras and oscilloscopes, to monitor the status of Elly and the other accelerated electrons. Some things to check on are location of the electron bunch (i.e. whether they are in center or off center of the beam line), intensity of the electron bunch (i.e. whether they are close together or have dispersed), and efficiency of the acceleration (i.e. whether the electrons received maximum help from the photons at the exact right time).

Cameras with television monitors provide an indirect mean to see approximately where the electrons are located. Bunch charge is a quantity that can indirectly measure intensity. A phase scan is a plot of quantum efficiency (percentage) versus set phase (in degrees). Quantum efficiency is the ratio of the number of electrons to the number of photons. A phase scan, as seen in figure 7, is performed frequently to see at which phase a maximum number of electrons will be accelerated with a minimum number of photons (i.e. where it costs less photons to get more electrons).

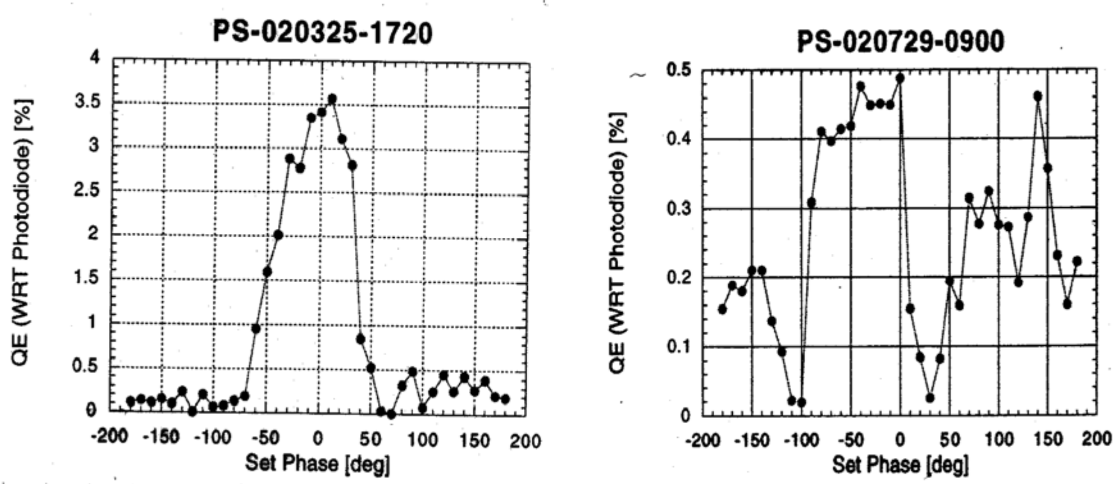


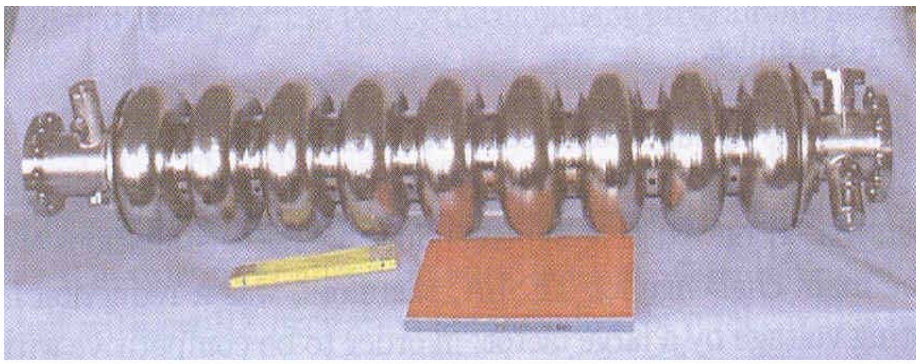
Figure 7. Left: Good phase scan showing one optimum phase. Right: Bad phase scan showing satellite noise.

The little Texan intern experiences good and bad moods (i.e. phases) all the time. The intern has noticed that when she has fewer problems (i.e. less noise) surrounding her, she correspondingly is in a better mood and can work more efficiently. Elly the electron behaves in a similar fashion. The people at A-zero do their best to eliminate the noise.

"Take three solenoids and call me in the morning." There are three solenoids that wrap around the cathode gun: the bucker, the primary, and the secondary solenoids. The job of these solenoids is to compress the accelerated electrons, focusing them into a round beam, and just basically keeping the electrons on the right track.

--Elly the Electron receives "super" powers--

If everything goes well with Elly's check up, she can proceed forward to her next journey, which is quite impressive. Ahead of her, Elly notices something familiar. She sees something similar to the 1.5 cavity cell in the cathode gun where she was first accelerated. However, Elly observes that something is different. Instead of there being just one cavity cell, there are nine of these cavity cells lined up back to back!



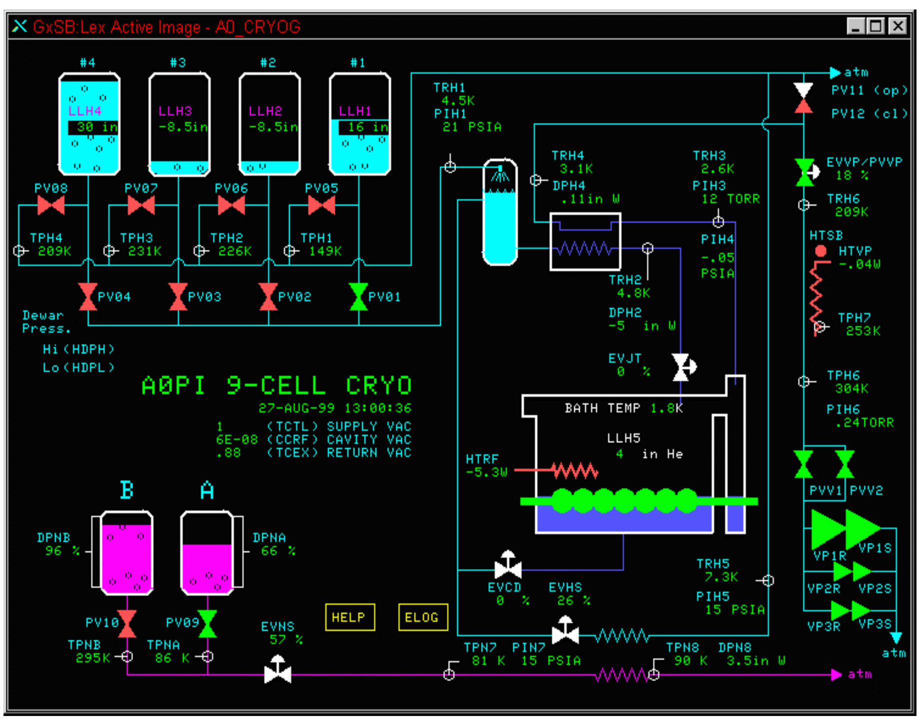


Figure 8. Top: Nine cell super-conducting cavity. Bottom: Labview interface to monitor the cryogenics needed for superconductivity.

Elly is overwhelmed. She can hardly believe that she will jump into a telephone booth (i.e. the nine cell super-conducting cavity) with an energy of ~4 MeV and come out with an increased energy of ~17 MeV. Elly loves superconductivity. For a normal conducting cavity, it would take ~12 megawatts of power to drive a gun with an energy gradient of 35MeV/meter. For a super-conducting cavity with the same energy gradient, it would take only 0.6 megawatts of power!

The impressive efficiency of the nine cell super-conducting cavity is due to the cryostatic properties of helium and nitrogen. If helium is pumped on, it is able to reach a temperature of 1.8 K at a pressure of 12 torr (see figure 8). The problem with helium is that it has a low vapor pressure, which means that it evaporates fairly quickly at even relatively low temperatures. For this reason, there are coils wrapped around the helium bath, where the nine-cell cavity is submerged, which are filled with nitrogen. These nitrogen-filled coils pre-cool the cavity so that the helium will not evaporate and remain cool in the liquid state. This setup provides for an excellent heat exchanger, which reduces wasted power and results in an almost zero resistance cavity—a super-conducting cavity.

The little Texan intern knows all about hot conditions and the energy it soaks up. She is grateful for air conditioning, which is what the nine cell is for Elly the electron. However, Elly's air conditioner is much more sophisticated because of her high energy level that needs to be cooled off.

The nine cell super-conducting cavity has its own klystron that provides RF somewhat like the klystron/RF system for the cathode gun. However, there is one major difference—size. The cathode gun's klystron is larger (see figure 9) mainly because of the higher efficiency of the super-conducting nine cell cavity previously mentioned. Although the nine cell has advantages due to superconductivity, it is still quite difficult to time the RF phase precisely with the position of the electrons in order to optimally accelerate the electrons forward (and not backward).

Figure 9. Left: 200 kW klystron for the super-conducting nine-cell cavity.
Right: 3 MW klystron for the RF gun.

--Elly the Electron receives direction and focus--

Elly the Electron has reached higher levels of acceleration and energy as well as maturity. She is less susceptible to causing emission problems such as wanting to diverge from the beam line (space charge), as she was known to do before. However, as the intern has come to realize that as one passes with time and experiences different distractions, the need for drive and inspiration becomes more and more pertinent.

The same applies to Elly. According to Einstein's $E = mc^2$, as Elly receives more energy she also receives more mass which calls for stronger magnets to keep her in line and in focus. Dipole magnets are used for bending and are analogous to mirrors, while quadrupole magnets are used for focus and are analogous to lenses.

Dipole magnets consist of a north and south pole that steer the beam by bending it to the left or to the right. Quadrupoles, on the other hand, consist of two sets of north and south poles: one set of poles in the vertical direction and one set of poles in the horizontal direction. One quadrupole can focus in only one direction therefore more than one quadrupole is needed to focus in both directions. A positive current induced in one quadrupole will provide for vertical alignment while defocusing in the horizontal direction. A negative current induced in the following quadrupole will provide for horizontal alignment while defocusing in the vertical direction.

Quadrupole magnets focus in the transverse plane i.e. focus in the dimension of space. The chicane, as pictured in figure 10, consists of four dipole magnets steering the beam down, straight, up, and then straight again to the previous level of the beam line. The purpose of this chicane is to focus the beam in the longitudinal direction (the direction of electron flow) i.e. focus in the dimension of time.

Being able to focus in the dimension of time has been a great challenge for the little Texan intern. This level of focusing requires one to set priorities so as to not waste time. The intern has always tended to go to the extremities just the way Elly frequently creates emittance problems. To live in balance seems impossible for the intern, which is why she can understand why it takes four large magnets (i.e. the chicane) to focus Elly in the dimension of time.

Figure 10. Chicane (compression) magnets in the beam line.

--Elly the Electron lends her services--

A picture of Elly and the other accelerated electrons at the end of the beam line can be seen in figure 11. This picture is made possible with a device called a spectrometer magnet. By varying the current on a particular parameter page, the magnetic field changes thereby increasing or decreasing the energy needed to bend the electron beam. A correlation of $E_T = \text{sqrt}((1.54 * I_{spec})^2 + 0.511^2)$ is used to determine the total energy of Elly and her accelerated electron bunch given a current at the end of the beam line.

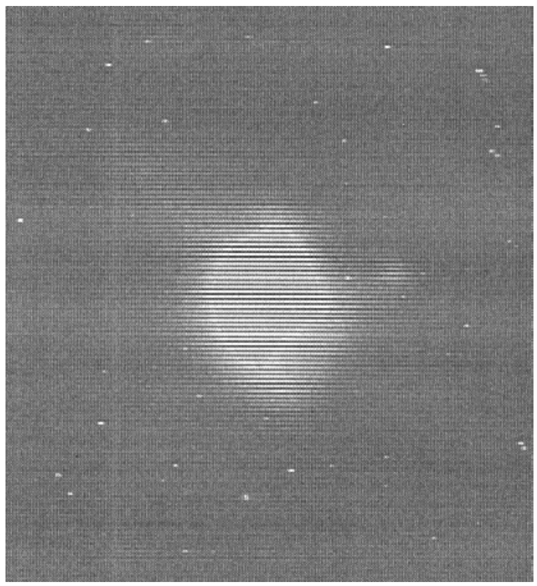


Figure 11. Picture of the electron beam at the end of the line.

There is a point in time when we review our life and hope that somehow we have made a difference. Elly the Electron has much of these same feelings when she reaches the end of the beam line. Elly remembers all the insecurities that she had in the beginning and feels like she has not really contributed since then. She thinks to herself "What have I done to deserve such accelerating treatment?"

However, the list of studies, research projects, diagnostics and end user effects that Elly the Electron has made possible with her sole existence is quite respectable. Some examples of research topics include flat-beam "optimization," Plasma-Wakefield Acceleration, Super-conducting RF cavities, and Fundamental Studies of Space Charge. Also remarkable treatments for diseases have been made possible by studying and using Elly along with the other accelerated electrons.

--The Texan intern lends her services--

The intern constantly questioned herself on what she had done that allowed her to be here at Fermilab to witness such "accelerating" technology. Whatever it was she made herself work hard to show how much she appreciated the opportunity. A great amount of time was spent on an interferometer setup that the intern hopes to be of some use in the future.

An interferometer is set up at XL4 in the A0 Photoinjector beam line. A flag that is at a 45° angle with respect to the beam line is placed in the center of a six way cross at XL4. Coherent Transition Radiation (CTR) light is reflected off the flag and into one of the side arms of the six-way cross. The CTR light then passes a window viewport made of crystalline quartz because crystalline quartz goes farther into the infrared region (i.e. longer wavelengths) than fused silica. The viewport required a custom-designed tube insert (see figure 12) such that an optimal amount of light could be obtained for the interferometer setup.

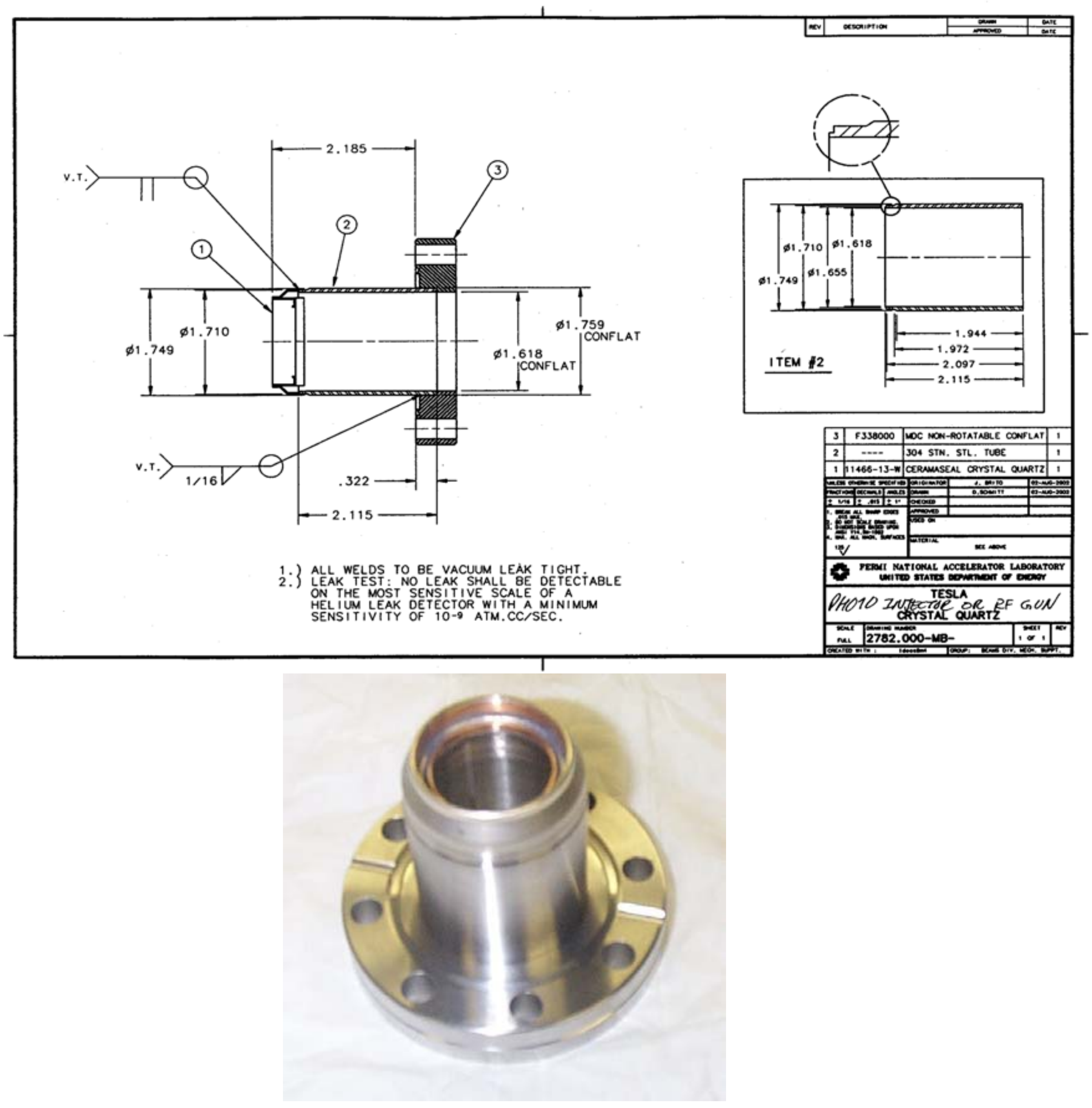


Figure 12. Top: Drawing of recessed tube view port design.
Bottom: Actual viewport constructed.

Uwe Happek from the University of Georgia is the designer of the interferometer, which is an instrument that measures the longitudinal width of an electron bunch. Uwe states in his paper that the longitudinal width of an electron bunch is an important parameter for both free electron lasers (FELs) and next-generation of high energy facilities, e.g. linear colliders. For FELs, the bunch length strongly influences the gain and in the case of linear colliders, wakefields depend on the bunch shape and are a limiting performance factor. Despite the importance of the longitudinal electron distribution within a bunch, experimental access to this parameter has been difficult.

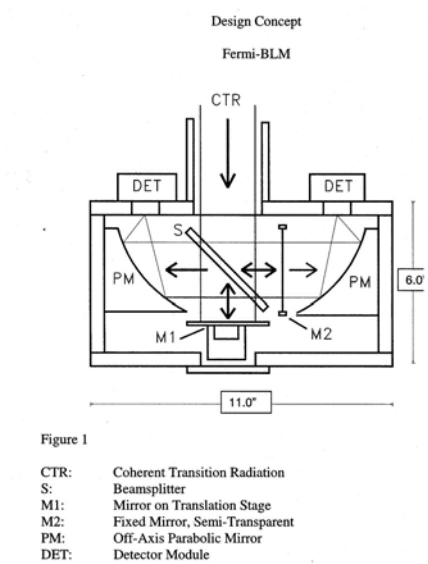


Figure 13. Schematic of Uwe Happek's interferometer design.

Coherent Transition Radiation (CTR) light enters the interferometer and hits a beamsplitter (see figure 13). Half of the CTR light source is reflected at a 90-degree angle to the right and the other half of the CTR light source is transmitted to a mirror on a translation stage below the beamsplitter. A translational stage is used in order to vary the path distance of one of the CTR light sources. This difference in path distance will create interference patterns that will be used to determine bunch length. A driver controls the translational motor stage with a small keyboard (see figure 14) thereby allowing for remote access. Some work went into calling the manufacturer to decipher the program code required to make the stage move.

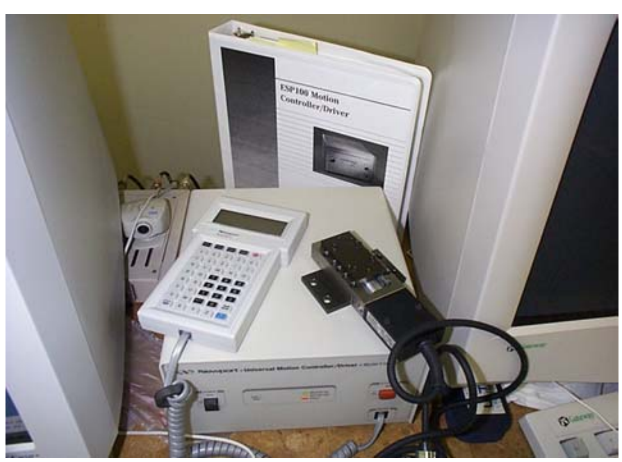


Figure 14. Picture of controller /keypad /translation motor stage system.

The fifty percent of CTR light that goes toward the right passes through a fixed, semi-transparent mirror that allows a fraction of it (~50 %) to pass which means that the CTR light source is reduced to approximately a quarter of the original light. This fraction of CTR light then hits a parabolic mirror, which directs the CTR light into a detector.

The other fifty percent of CTR light that heads down toward the mirror on the translation stage previously mentioned hits the mirror and is reflected back up toward the beamsplitter. The beamsplitter then splits the CTR light up again, reducing the beam from 50% to 25% of the original, incoming CTR light. From the beamsplitter the CTR light heads left at a 90-degree angle towards another parabolic mirror that also directs the CTR light into another detector.

Both detectors receive approximately 25% of the original CTR light that comes into the interferometer. Both detectors also use an inverse Fourier transform to reflect the shape of the electron distribution in the bunch. Theoretically, with this shape, the longitudinal bunch length can be determined.

The interferometer needs to be mounted securely so that no vibrations disturb the diagnostics. For this reason a 6-inch by 12 inch by 1 inch thick anodized, aluminum platform was designed, machined, and polished by the intern (see figure 15). This platform, along with some kinematic mounts, was shipped to Uwe Happek in Georgia. (Note: Thanks to Daniel Snee the intricate welding of the viewport to the tube insert and the machining of the platform were a success).

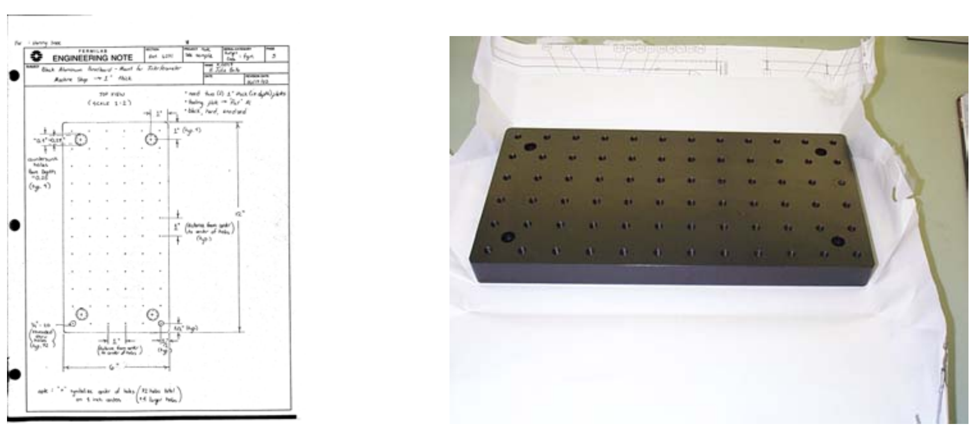


Figure 15. Left: Sketch of platform with measurements. Right: Finished platform.

Conclusion:

Although Elly the Electron and the Texan intern feel somewhat tiny in the huge scheme of things, they try their best to help out in any way possible. It is very easy to get lost when a great amount of new information is presented. Numerous computer monitors, controls, and switches surrounding the environment do not help the matter at all (see figure 16). Due to the complexity of the situation, it is quite exhilarating to find one little thing that you understand. Also the excitement that comes with turning on the gun, varying parameters, monitoring reactions, and understanding even only a few results is irreplaceable. Time to better understand exactly what is happening is one thing that is lacking.

Figure 16. Left: Equipment gallery. Right: Control room.

Elly and the intern are nevertheless grateful to all those who have helped them accelerate to higher levels. Elly and the intern only wish to have been able to give back more. Elly, by being herself, has done her part in providing a means to study physics more closely and in different ways. The little Texan intern can only hope that "ya'll" there at Fermilab will remember a southerner that worked hard and appreciated every minute. She has no doubt that the little physics she learned at A0 Photoinjector lab will be applicable to the wide range of developing fields in Biomedical Engineering, the intern's future goal. The little Texas intern anticipates that what she has experienced at Fermilab can be used for future reference in order to add to the great effect that science has made in life.

Acknowledgements:

I would like to thank the SIST committee, especially Dianne Engram and Dr. Davenport, for giving a little southerner an opportunity to accelerate. Meeting different people is always a pleasure. However, my co-workers at A0 Photoinjector Lab are one of a kind: Chris Johnson—great coach; Kai Desler—motor bike buddy; Kip Bishofberger—Californian stud; Wade Muranyi—thanks for making me smile S.P.; Mike Heinz—flying ice specialist; Rodion Tikhoplav—what's up; Nick Barov—best dresser; Yang Xi—encouraging supporter; Court Bohn—honorable theorist; Yin-e Sun—you are my sunshine; Eric Thrane—go Michigan State, just kidding; Daniel Mihalcea—simulation worker bee; Helen and Don Edwards— admirable intellectuals. Special thanks goes to my supervisor, Jaime Santucci, for his time, patience, and enthusiasm—ya'll fix'in to make me take out a can of whoop booties.

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