SLAC-PUB-9354
August 2002

Development of an X-band RF Gun at SLAC*

A. E. Vlieks*, G. Caryotakis*, W. R. Fowkes*, E. N. Jongewaard*,
E. C. Landahl‡, R. Loewen* and N. C. Luhmann, Jr.‡

**SLAC, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA*
‡ 3001 Engineering III, Dept. of Applied-Science
Davis, CA 95616, USA

Abstract. As part of a National Cancer Institute grant to develop a compact source of monoenergetic X-rays via the Compton Effect, we have completed the design of a Laser-driven 5.5 cell RF gun operating at 11.424 GHz. The goal is to develop an RF Gun which can generate a 7 MeV, 0.5nC electron beam with an RMS emittance of $\simeq 1\ \pi$-mm-mR. We have completed simulations of the total beamline, including the RF gun, accelerator structure, focusing quadrupole triplet and electron beam/laser beam Interaction Region using PARMELA. Results of these simulations will be presented, showing that a 60 MeV electron bunch can be focused to an interaction point two meters downstream of the photocathode. We will also present results of RF measurements of the Gun-cold-test model showing the field distribution along the gun axis and the gun resonances. Details of the RF power Source, Emittance-Compensating Solenoid and Laser system will also be presented

INTRODUCTION

One of the proposed methods of identifying and destroying certain types of cancer cells is through the use of tunable monochromatic X-Rays [1]. Heavy elements such as Iodine, Gadolinium or Gold can be introduced near or in cancer cells by attaching them to specially designed molecules, which are selectively absorbed by tumors. By irradiating these cells with X-Rays at the K-shell energy of the heavy element, the absorption cross section for these elements is enhanced relative to the neighboring tissue. If a second X-ray image is taken at an energy below the K-shell energy and subtracted from the first image, the resulting image spotlights the heavy element and. thereby helps to identify the location of the tumor. A higher X-Ray flux can be used to selectively destroy these cells. This technique has already been investigated in large Synchrotron facilities [2].

We are working on the development of a tunable X-ray source using the Compton effect to upshift the energy of a high power laser beam into the X-ray region using a low emittance electron beam as the energy source. In our setup, shown in figure 1, a 7 MeV electron beam is generated by a 5.5 cell X-band RF gun, operated at X-band, and driven by a UV laser. The beam energy is increased up to 60 MeV using a 1.05 m X-band accelerator. Finally it is focused to a minimum spot size at the Interaction Region where it collides, nearly head-on with a high power 800 nm laser beam, and generates X-rays to energies up to $\simeq$ 87 KeV.

* Work supported by Department of Energy contract DE-AC03-76SF00515

Presented at the RF 2001 Workshop, Snowbird, UT., 10/1/2001 - 10/5/2001

The electron beam is then removed from the beamline axis with a spectrometer into a beam dump. A pair of 50 MW klystrons is used as high power RF sources. One klystron will feed the RF gun while the second will drive the accelerator. Both are driven from a common signal generator to maintain phase coherence.
In this paper we will describe the details of the proposed experimental setup, simulations of the RF gun and RF measurements of a cold-test prototype.

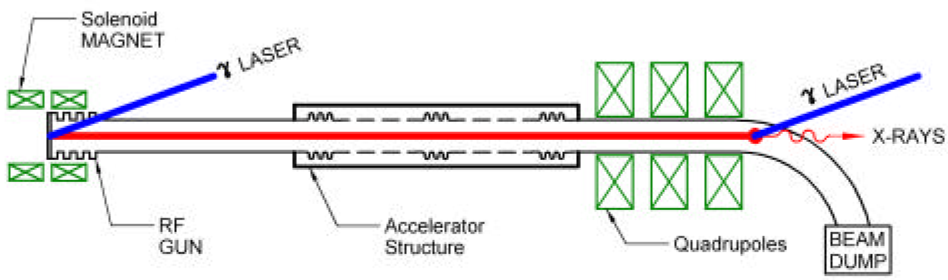


Figure 1. Schematic of Monochromatic X-Ray Source

EXPERIMENTAL SETUP

The design parameters of the gun are shown in Table 1. In order to attain an electron beam with energy of approximately 7 MeV with a maximum surface gradient of 200 MV/m we were required to design a gun with 5.5 cells. This number of cells is unique among rf gun designs. In many rf gun designs, performance is often limited by RF breakdown at the boundary where the demountable cathode fits into the gun. In our initial configuration we will not use a demountable cathode but instead use the whole back wall of the half-cell as the cathode. It will be made from OFE copper and machined to a micron-level surface flatness.

Beam Energy at gun exit (for 200MV/m gradient)	7 MeV
Bunch Charge	0.5 nC
Transverse emittance	1 π-mm-mR
Laser spot size at cathode (radius)	0.5mm
Laser temporal length	800 fs
Beam spot size at Interaction Region (radius)	20 microns
Beam energy at Interaction Region	60 MeV

Table 1. Gun Design Parameters

A (nominally) 6 KG magnet has been designed using POISSON [3] to serve as the emittance-compensating solenoid. The magnet is designed as two identical pairs operated so that there is exactly zero magnetic field in the center where the cathode will be positioned. This is shown in figure 2.

The gun laser beam, operating at 266nm, the third harmonic of a Ti:Sapphire laser, is directed towards the cathode at nearly normal angle of incidence after being deflected by a fixed mirror in a diagnostic chamber (located approximately .5 m downstream of the gun). All adjustments to the laser beam are performed external to the vacuum envelope. The current design calls for a dielectric mirror but metallic mirrors will also be investigated. A second mirror, symmetrically located with respect to the beam axis, is designed into the chamber to monitor the (cathode) reflected laser beam for diagnostic purposes

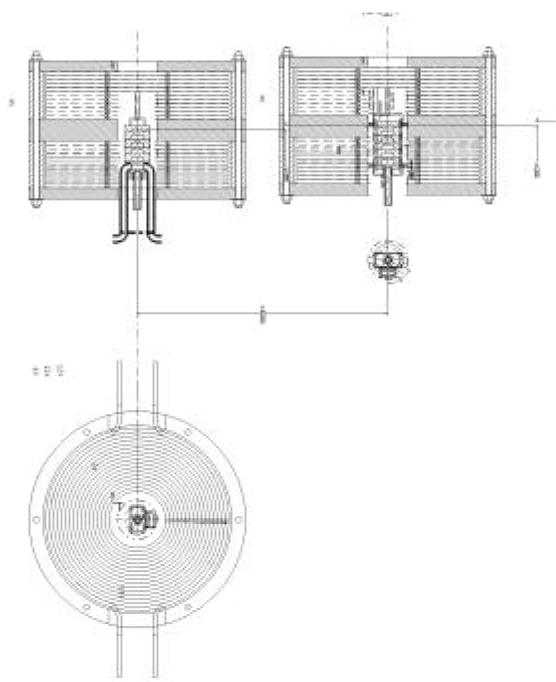


Figure 2. Emittance Compensating Solenoid

The chamber is shown in figure 3. Besides serving as a holder for the laser mirrors it also permits the insertion of various diagnostics (e.g. YAG crystal, OTR foils, pepper pot masks etc.) into the beam and contains a view port for observing the beam profile with CCD camera.

A 1.05 m accelerating structure is positioned approximately 67 cm downstream of the cathode. This structure is a $2\pi/3$ traveling wave structure. This structure has been successfully conditioned to approximately 75 MV/m (accelerating gradient) during Next Linear Collider (NLC) breakdown studies. For our purposes we will only need a maximum accelerating gradient of approximately 53 MV/m. The RF power requirement at this gradient is approximately 40 MW.

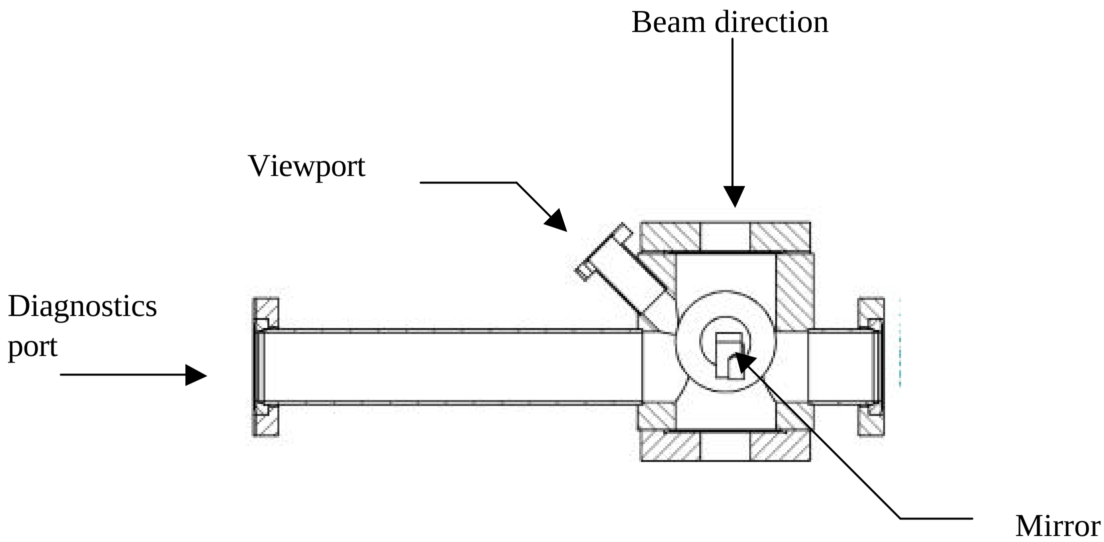


Figure 3. Diagnostic Chamber

Downstream of the accelerator is located a triplet of quadrupoles which will focus the beam to a spot size of ~20 microns in the interaction chamber (not shown in fig.1).

SIMULATIONS

The gun cavities were designed to operate at 11.424 GHz in the π-mode using the code SUPERFISH[3]. Results of these simulations, shown in figure 4, indicate that approximately 16 MW of RF power will be required to develop the peak design gradients at the cathode. Power will be fed into the gun through symmetric ports in the last (most down-stream) cell in order effectively remove the dipole asymmetry present in a single feed coupler. The design of this cell required 3-d simulations. MAFIA[4] and HFSS[5] were used for this purpose. The coupling ratio, β, was chosen to be 1.8 in order to shorten the RF filling time to 60 ns. The RF pulse width will be 150 ns or 2.5 filling times.

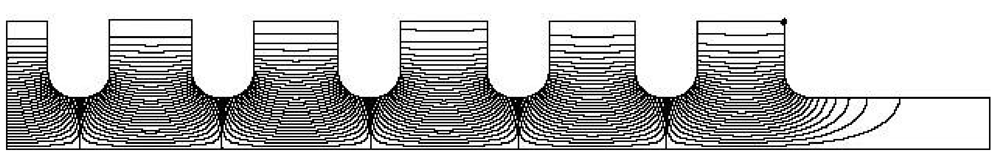


Figure 4. SUPERFISH simulation of RF gun

Many PARMELA[6] simulations were used to fine-tune the dimensions of the RF gun as well as optimize the field strength of the Solenoid for minimal transverse emittance It was also used to optimize the location of the accelerator and determine the relative field strengths and locations of the quadrupole triplet for a minimal spot size at the Interaction Region. An early example of these simulations is shown in figure 5. which shows the behavior of the beam profile along the beam axis.

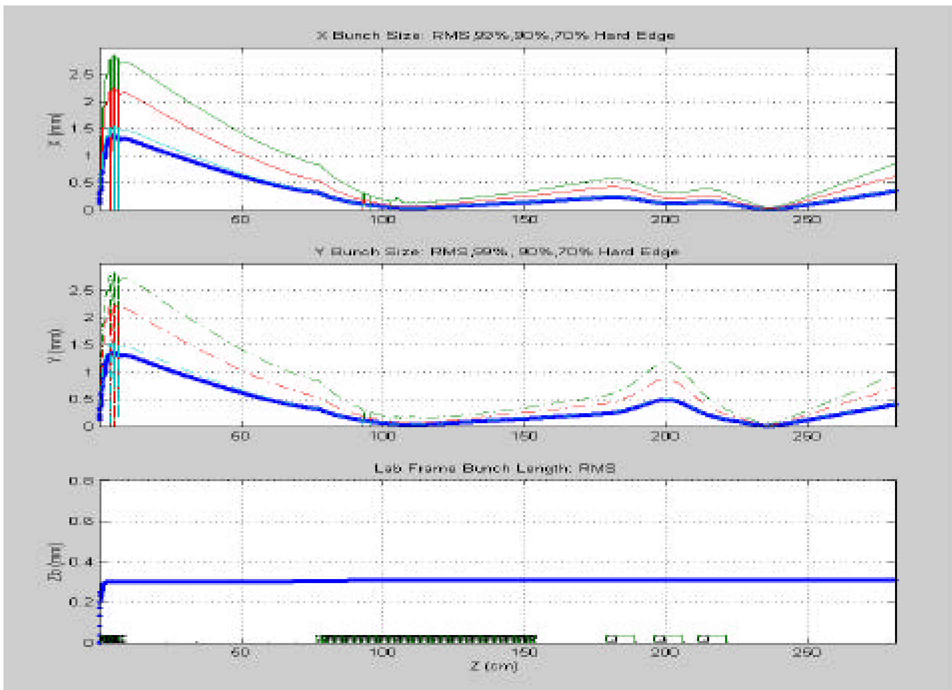


Figure 5. PARMELA simulation of RF gun

In this simulation the emittance at the interaction point was ~1.4 π-mm-mR with an RMS radius of ~14 microns. The shape of the pulse was nearly ideal (beer-barrel) with duration of .5ps and a cutoff radius of .25 mm (defined below). Because the laser energy density at these dimensions exceeded the damage threshold for copper [7], both the pulse width and duration were doubled in later studies. This change had the beneficial results that the gun could be operated well below the damage threshold and the quality of the beam could be improved. Further simulations, using more realistic (Gaussian) pulse shapes, resulted in good emittance beams at the Interaction Region. Table 2 shows a comparison of emittance for a beam with an initially "flat " shape with that of a Gaussian shape. [Note that in PARMELA, the initial beam shape, both temporally and transversely, is defined in terms of a Gaussian rms width, σ, and a cutoff width, σ_c . A flat beam is obtained by making $\sigma >> \sigma_c$. (Even for $\sigma = 2*\sigma_c$ the pulse shape is nearly flat).]

The effect of magnet transverse offset was also investigated. Using an option in our version of PARMELA we were able to displace the magnet transversely and observe the displacement of the beam centroid as well as the emittance change. The values were determined at the waist of the beam. The results are shown in figure 6. It is interesting to note that for a magnet displacement $\leq$ 0.005 inches there is considerable beam centroid displacement (600 microns) but very little emittance degradation This would indicate that corrector coils could be used to bring the beam back on-axis as it enters the accelerator.

	"Flat" Beam	Realistic beam
σ(radial)	1.0mm	0.25mm
σ_c(radial)	0.5mm	0.5mm
σ(temporal)	0.8ps	0.2ps
σ_c(temporal)	0.4ps	0.4ps
Emittance (rms)	0.72 π-mm-mR	1.1 π-mm-mR
Beam radius at Interaction Region	11.6 μ	22.6μ

Table 2. Comparison of beam characteristic at interaction region for different initial beam profiles.

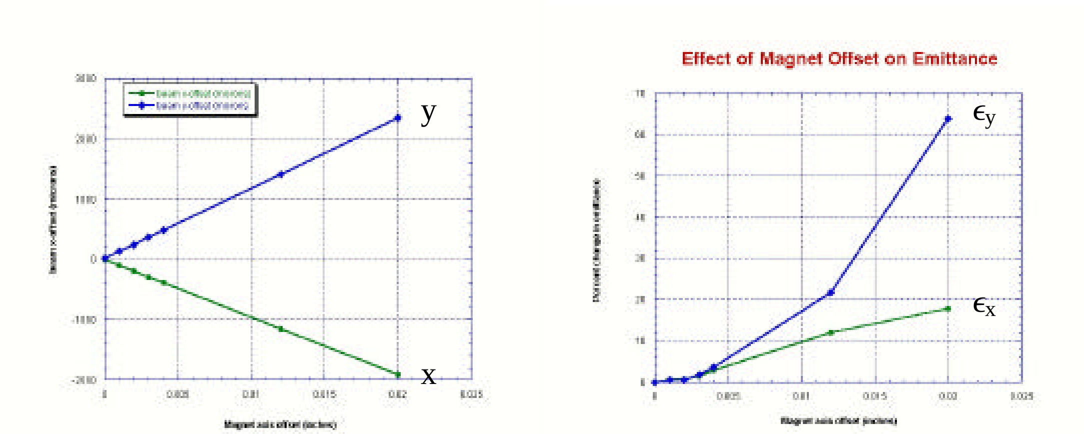


Figure 6. Effect of magnet offset on beam steering and emittance

COLD-TEST PROTOTYPE

A complete set of copper parts was fabricated using the dimensions obtained from SUPERFISH and MAFIA. Also fabricated were a pair of end caps, which permitted frequency measurements of individual cells. Half-cell end caps were first tuned so that the π-mode resonant frequency was 11.424 GHz and then used as matching cells for the other cells. The procedure is shown in figure 7.

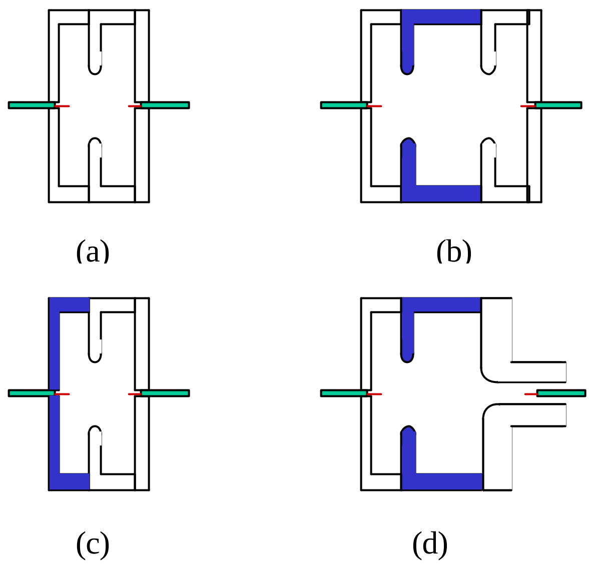
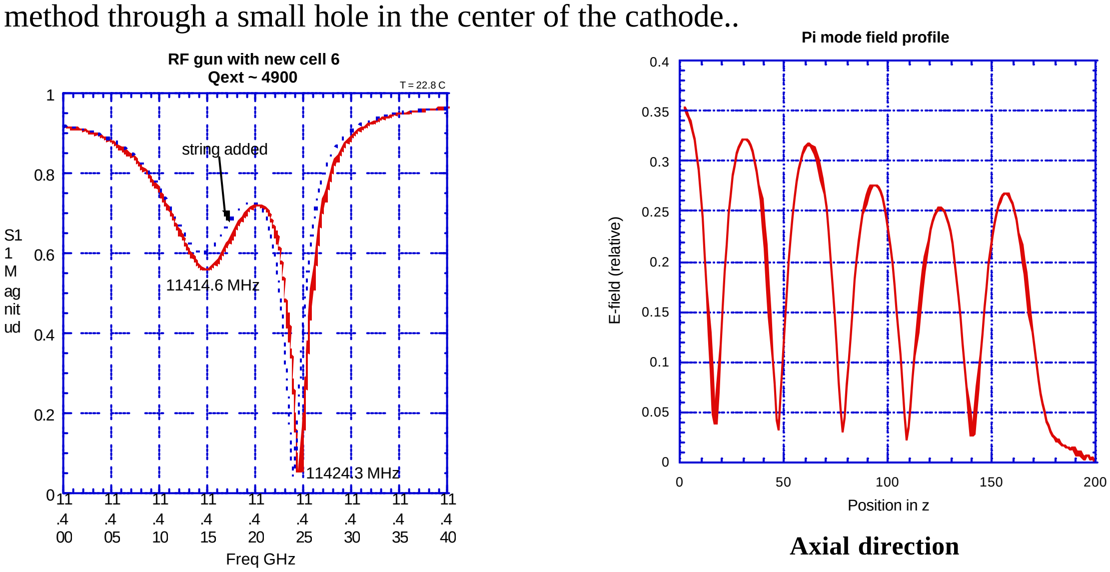


Figure 7. Sequence of cavity tuning. (a) Special end caps are tuned.(b)cells 2-4 are tuned individually. (c) Cell 1 (half-cell) is tuned. (d) Coupler cell is tuned. Coupling irises are not shown. The RF is coupled into/out of the cells by coaxial cables

After completion of this tuning, the cells were assembled as a unit and remeasured. The coupler cell was then tuned to correct the external Q. The resultant resonances and field profile is shown in figure 8. The field profile is obtained using the "bead-pull" method through a small hole in the center of the cathode..



(a) (b)

Figure 8. Structure before bonding. (a) Frequency spectrum. (b) Spatial field profile

In order to find out whether the cavity properties would change with bonding, the cells were high-temperature bonded and waveguides were brazed into the gun. The final cold test measurements are shown in figure 9.

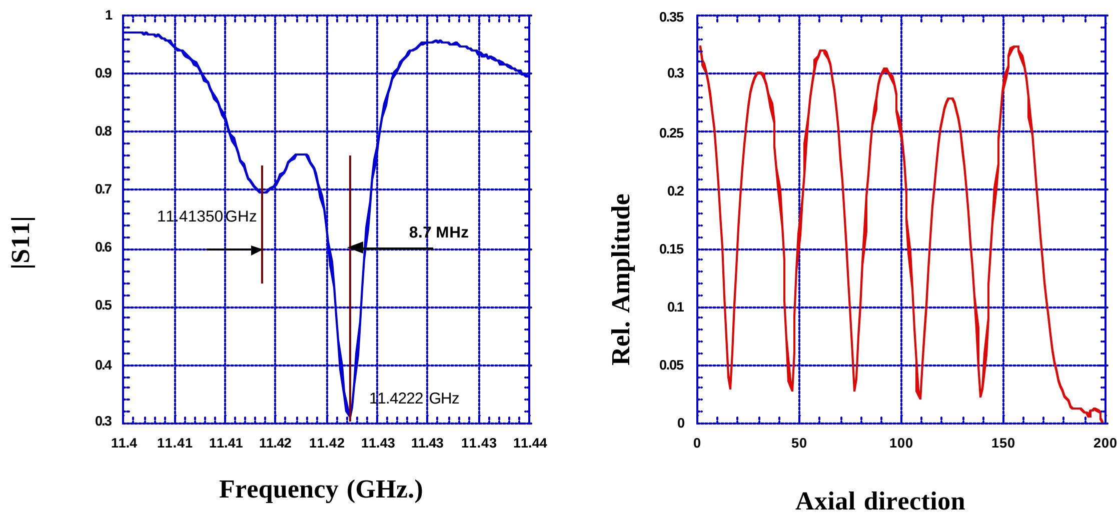


Figure 9. Structure after bonding

As can be seen from figure 9, the main change to the structure after bonding/brazing was an overall frequency shift of 2 MHz. This effect has been taken into consideration in the final gun dimensions.

SUMMARY

A 5.5 cell X-band RF Gun is being developed at SLAC as part of the development of a compact monochromatic X-ray source. Simulations using SUPERFISH and POISSON have been used to design the RF properties of the cavity cells and Solenoid magnet. MAFIA and HFSS were used where 3-d effects were present. PARMELA has been used to simulate and optimize the beam properties of the complete system. A cold-test prototype has been built and has been tuned to operate at the correct frequency and with a flat RF profile. The resultant dimensions will be used in constructing a working rf gun in the near future.

ACKNOWLEDGMENTS

One author,(aev) would like to thank Dr. E. Colby for his helpful suggestions and support throughout development of this work. We would also like to thank Dr. Cho Ng for his assistance with MAFIA simulations.

REFERENCES

[1]] Solberg, T.D., A. Norman (2001). "Monoenergetic x-rays improve the therapeutic ratio in x-ray phototherapy of brain tumors." *Proceedings of the Workshop on the Medical Applications of Synchrotron Radiation*, Grenoble, France, March 1 – 3 2001

[2]E. Burattini, "Synchrotron Radiation: A new trend in X-Ray Mammography", *ACTA Physica Polonica*, **A91**(4), 707-713, (1997)

[3]: James Billen and Lloyd M. Young, *POISSON, SUPERFISH reference manua*l, LA-UR-96-1834.

[4] R.Klatt, F.Krawczyk, W.R.Novender, C.Palm, T.Weiland, "MAFIA- A three-Dimensional Electromagnetic CAD ystem for Magnet, RF Structures and Transient Wake-Field Calculations", *Reports at the 1986 Linac Accelerator conference*, Stanford, USA June 2-6,1986

[5] Agilent High-Frequency Structure Simulator v5.6, *reference manua*l 85180-90194

[6] Lloyd Young, PARMELA *reference manual*, LA-UR96-1835,January 8,2000,. The version of PARMELA used in this work is a modified version of PARMELA due to E. Colby, at SLAC.

[7] T. Srinivasan-Rao, J. Fischer, and T. Tsang, "Photoemission studies on metals using picosecond ultraviolet laser pulses", *J. Appl .Phys*. **69** (5) 1 March 1991, 3291-3296.