

## PROGRESS REPORT

### Investigation of Novel Schemes for Injection/Extraction Kickers (LCRD 2.22)

#### **Personnel and Institution requesting funding**

University of Illinois at Urbana-Champaign, Department of Physics:  
George D. Gollin, Michael J. Haney, Guy Bresler, Joseph Calvey, Jason Chang, Keri Dixon, Michael Davidsaver, Justin Phillips

#### **Collaborators**

Fermi National Accelerator Laboratory:  
David A. Finley, Chris Jensen, Vladimir Shiltsev

Cornell University, Department of Physics:  
Gerald F. Dugan, Mark Palmer, David L. Rubin

Collaborating personnel will work on the project but are not requesting funding here.

#### **Project Leader**

George Gollin  
[g-gollin@uiuc.edu](mailto:g-gollin@uiuc.edu)  
(217) 333-4451

#### **Project Overview**

The 2820 bunches of an ILC pulse would require an unacceptably large damping ring if the 337 ns linac bunch spacing were used in the damping ring. As a result, the TESLA 500 GeV design<sup>1</sup> called for 20 ns bunch separation in a 17 km circumference damping ring; a kicker system would deflect individual bunches on injection or extraction, leaving the orbits of adjacent bunches in the damping ring undisturbed. Faster kickers would allow the operation of smaller damping rings, and progress on kicker technologies has been rapid.

---

<sup>1</sup> TESLA Technical Design Report, [http://tesla.desy.de/new\\_pages/TDR\\_CD/start.html](http://tesla.desy.de/new_pages/TDR_CD/start.html) (March, 2001).

The ILC damping ring group's baseline configuration document conveying its recommendations to the Global Design Effort<sup>2</sup> is nearing completion. It calls for ~6 km circumference rings using "conventional" stripline kickers driven by fast HV pulsers. But "because Fourier pulse-compression kickers provide a very different approach, it is worthwhile continuing studies to develop a more complete understanding of the benefits and limitations of these systems."<sup>3</sup>

We are working on both approaches to fast kickers, studying stripline kickers using the 16 MeV electron beam available at Fermilab's AØ photoinjector facility, as well as modeling a Fourier series kicker module that will be built in collaboration with the FNAL RF group. Our initial goals are to determine the suitability of the AØ beam for precision kicker studies and to measure the amplitude and timing stability of a simple kicker as well as can be done at AØ. This will allow us to understand our prospects for testing a Fourier series kicker module at Fermilab; we hope to move from modeling to implementation of such a module in 2006.

## Progress Report

### *Stripline kicker studies using Fermilab's AØ 16 MeV electron beam*

Engineers in Fermilab's Technical Division designed and built a stripline kicker for us in 2005. The device's parallel electrodes are approximately 26 cm long and separated by 1 cm. The electrodes form a 100 Ω transmission line which contains the kicking electric and magnetic fields. Two high voltage pulses of opposite polarity travel through coaxial hardline cables to enter the kicker vacuum vessel through HV feedthroughs attached to the electrodes. The pulses propagate along the electrodes in the upstream direction, leaving the kicker through another pair of feedthroughs to travel through standard coaxial cables that are properly terminated. Photographs of the partially assembled kicker are presented in Figure 1.

Design of the kicker was guided by detailed simulation of the device's electrodynamic properties, included the modeling of the electrode support structure and vacuum vessel. Though our initial studies would employ an available high voltage pulser with the relatively slow rise time of 10 ns, we wanted the kicker to work acceptably well with the faster rise times possible with a FID (Fast Ionization Dynistor) pulser. The simulations showed that close attention to the geometry of the electrode support structure was important. In particular, the capacitive path from the electrodes to the wall of the vacuum vessel provided by the posts holding the electrodes determined the frequency of a resonance that could cause signals to be reflected from the HV feedthroughs, rather than entering the vacuum vessel.

---

<sup>2</sup> *Recommendations for the ILC Damping Rings Baseline Configuration*, [http://www.desy.de/~awolski/ILCDR/DRConfigurationStudy\\_files/DRConfigRecommend.pdf](http://www.desy.de/~awolski/ILCDR/DRConfigurationStudy_files/DRConfigRecommend.pdf), draft dated December 20, 2005.

<sup>3</sup> *Ibid.*



Figure 1. Kicker assembly. Left photo: electrodes, visible inside the vacuum vessel. Right photo: installing ion pumps.

Three different support structure geometries, labeled with the frequencies of their associated resonances, are shown in Figure 2. The frequency dependence of the reflection coefficients for these structures is shown in Figure 3. (Recall that a rise time of 1 ns corresponds to a frequency of about 0.5 GHz.) The version actually constructed is expected to behave similarly to the 2003 MHz version.

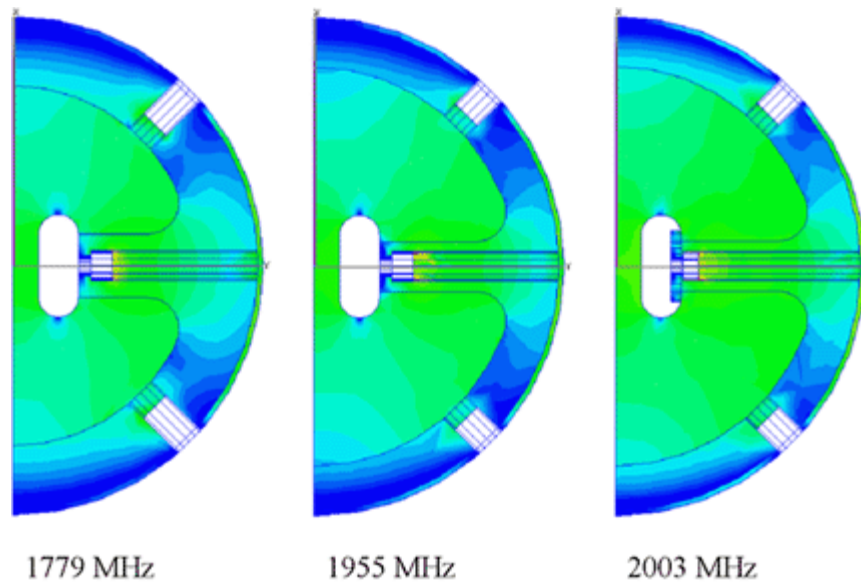


Figure 2. Study of the resonance properties of different electrode support geometries.

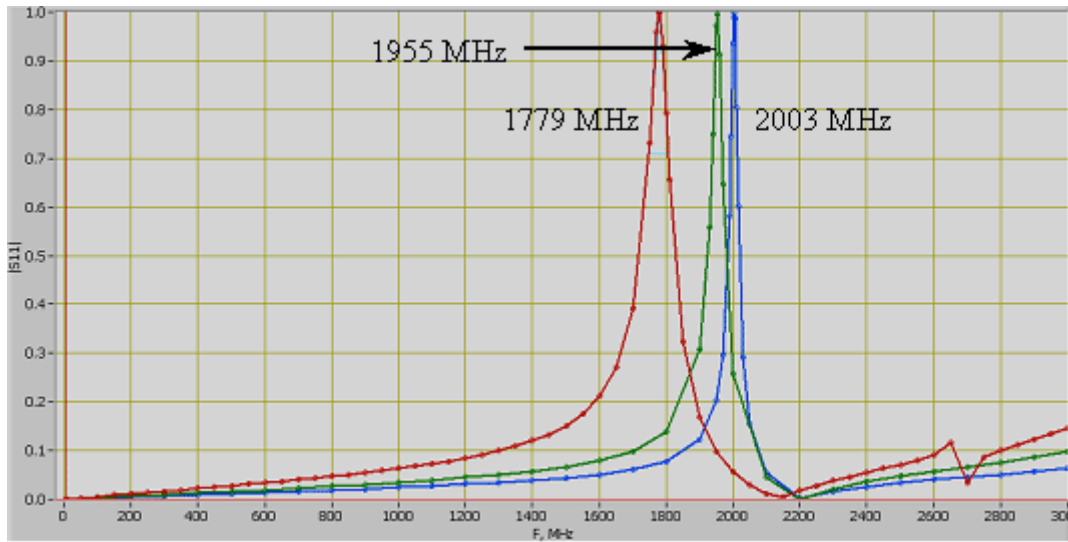


Figure 3. Frequency dependence of the reflection coefficients for the structures shown in the previous figure.

We used a  $\pm 750$  V pulser (identical in design to those used in the Fermilab linac chopper) to excite the kicker. The pulser's output, measured on the bench, is shown in Figure 4.

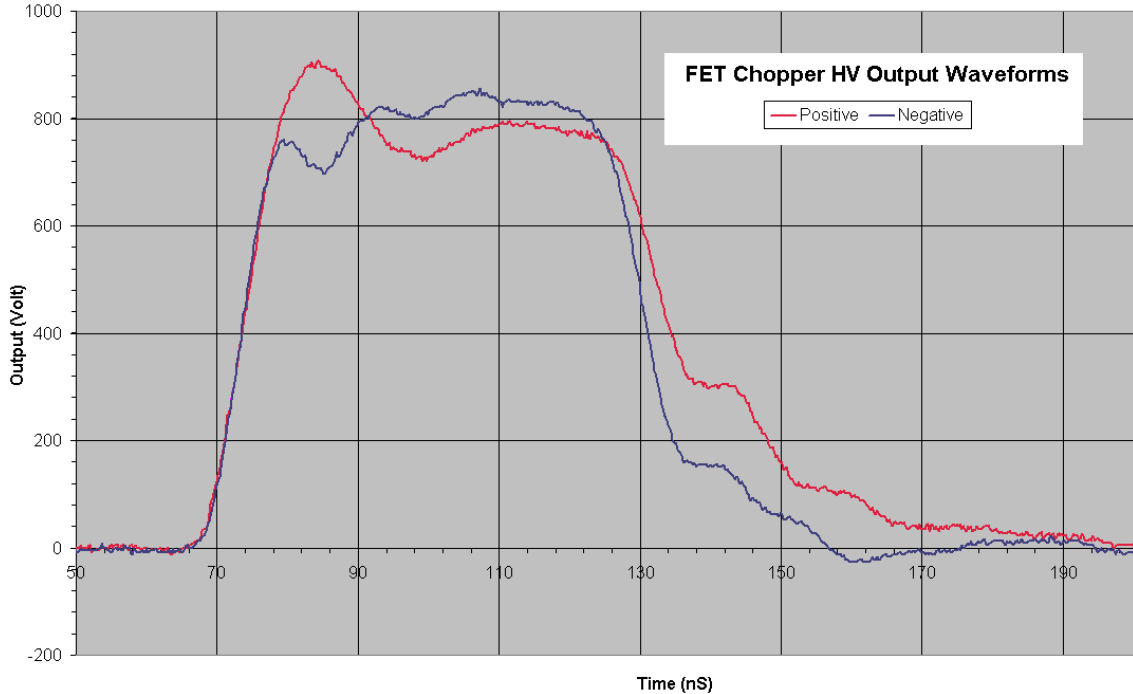


Figure 4. High voltage pulser outputs. We used this pulser to excite the kicker. Note that the negative pulse is inverted.

The AØ beamline in the vicinity of the kicker is shown schematically in the diagram of Figure 5. The beamline was instrumented with beam position monitors, a small steering magnet immediately downstream of the kicker, and a dipole spectrometer magnet. The kicker after installation at AØ is shown in Figure 6.

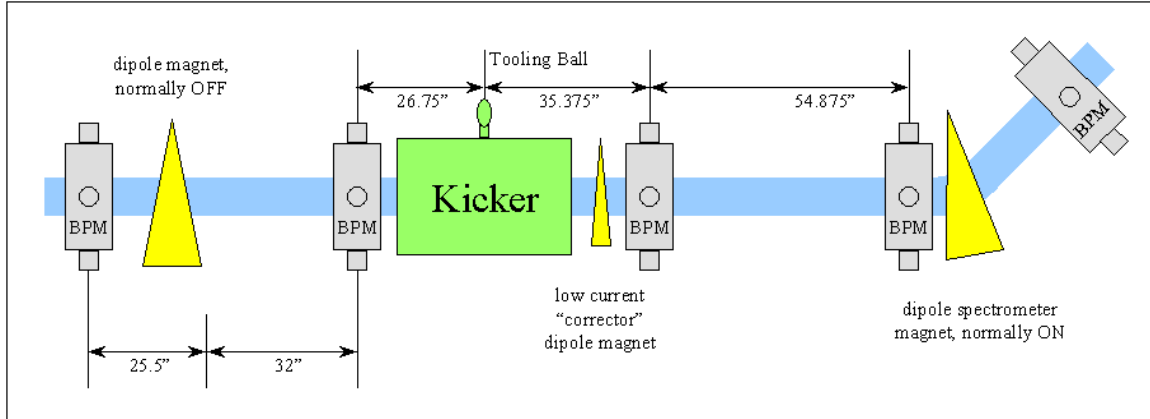


Figure 5. Approximate layout of the AØ beamline.

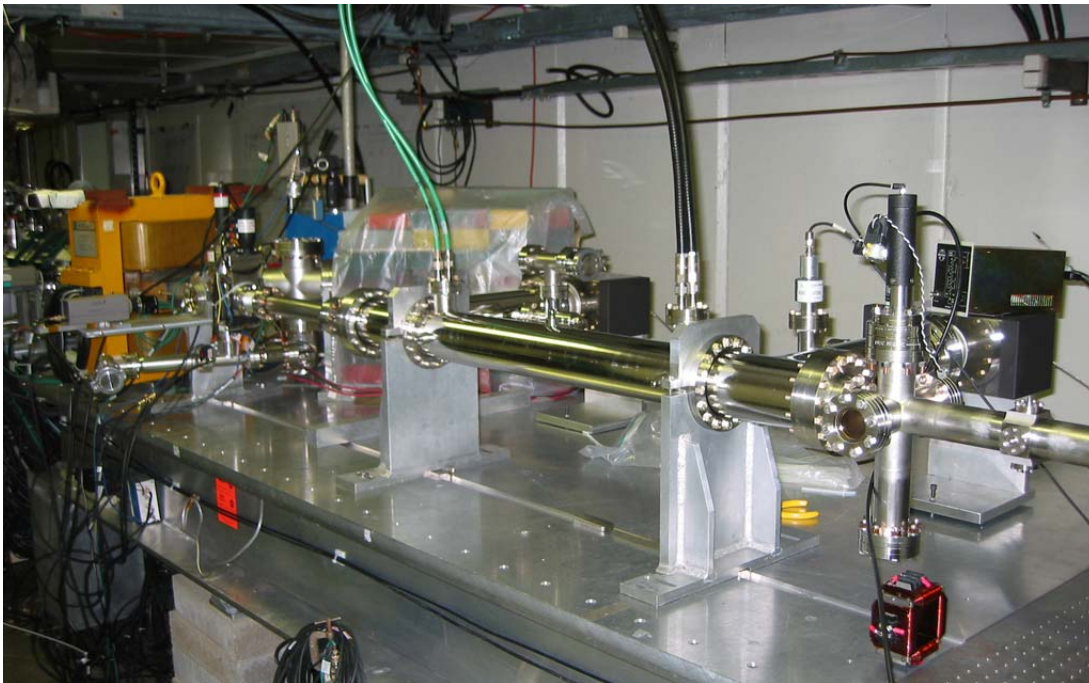


Figure 6. Looking upstream in the AØ beamline after installation of the kicker. High voltage pulses enter the kicker through the black cables visible near the downstream end of the kicker.

A “phase detector” (a small cavity in the beamline several meters upstream of the kicker) provided us with beam-induced signals that could be mixed with the beamline’s 1.3 GHz

master timing signal to determine the arrival time of electron bunches with great accuracy.

We installed the kicker and built a working data acquisition system during 2005, taking data for the first time in August 2005. We are presently analyzing the data from last August and expect to finish developing our various calibration and analysis tools during the spring of 2006.

Samples of what we work with are shown in Figure 7. The “lego plot” on the left represents the illumination profile in the BPM that is downstream of the spectrometer magnet. The oscilloscope traces on the right show signals from the kicker electrodes and phase detector. Normally the electrode signal displays the HV pulse, but in this particular run we had turned the HV supply off for alignment purposes. The negative pulses that feature prominently illustrate the response of the electrodes to the passage of a beam bunch. The phase detector oscillations induced by this pulse are shown in the third trace. The positions of peaks and zero-crossings in this trace allow us to determine the time of the bunch’s passage to an accuracy that is better than a few tens of picoseconds.

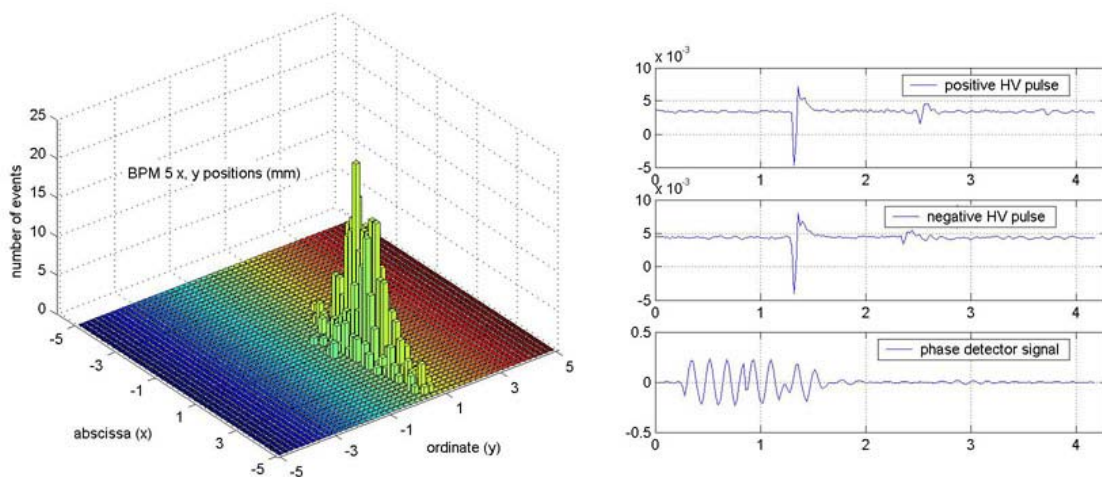


Figure 7. Data from AØ: beam profile in the last BPM (left); oscilloscope traces showing kicker electrode pickup of a passing bunch as well as induced oscillations in the “phase detector.”

#### *Fourier series kicker studies and preliminary RF investigations*

We described our modeling of a Fourier series pulse compression kicker in detail in last year’s *A University Program...*<sup>4</sup> A general discussion of a Fourier-series kicker system

<sup>4</sup> *A University Program of Accelerator and Detector Research for the International Linear Collider (vol. III)*, G.D. Gollin, editor, pp. 116–157, April, 2005. (Available on the web at [http://www.hep.uiuc.edu/LCRD/LCRD\\_UCLC\\_proposal\\_FY06/](http://www.hep.uiuc.edu/LCRD/LCRD_UCLC_proposal_FY06/).)

can also be found on the web.<sup>5</sup> We are focusing on a particular implementation in which an RF amplifier sends a broadband signal down a waveguide to a  $Q \approx 25$  RF structure. Dispersion in the waveguide shifts the relative phases of the Fourier components of the signal so that it is compressed: RF power arrives at the RF structure in short, periodic bursts, filling it in order to eject the target bunch without disturbing adjacent bunches. The RF structure is able to store energy, so its maximum field strength is approximately 20 times greater than the maximum field strength in the downstream end of the waveguide. A schematic representation of the kicker is shown in Figure 8. Our studies assume the values for the kicker's parameters shown in Table 1.

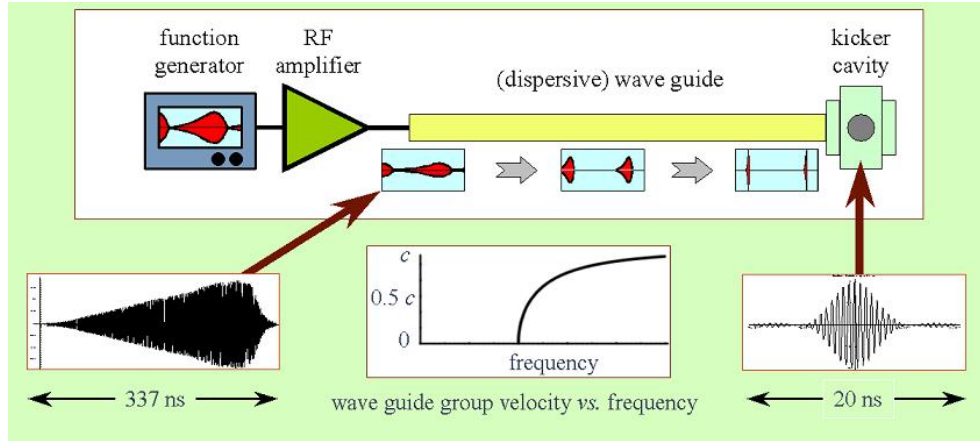


Figure 8: Schematic representation of a Fourier series pulse compression kicker.

Parameter	Symbol	Value
Main linac bunch frequency	$f_L$ ( $\omega_L \equiv 2\pi f_L$ )	3 MHz
Damping ring bunch frequency	$f_{DR}$ ( $\omega_{DR} \equiv 2\pi f_{DR}$ )	180 MHz
RF structure center frequency	$f_{RF}$ ( $\omega_{RF} \equiv 2\pi f_{RF}$ )	1845 MHz
RF structure $Q$	$Q$	25
Waveguide cutoff frequency	$f_{cutoff}$	1300 MHz
On field integral	$A(0)$	$(100 \pm .07)$ Gauss-meters
Off field integral	$A(t)$	$(0 \pm .07)$ Gauss-meters
$f_{DR}/f_L$	$N$	60
$f_{RF}/f_{DR}$	$\Gamma$	10.25
$f_{RF}/f_L$	$\Gamma N$	615
Bunch length	$\delta_B$ or $\tau_B$	$\pm 6$ mm $\sim \pm 20$ ps

Table 1: Fourier series pulse compression kicker parameters.

<sup>5</sup> George D. Gollin and Thomas R. Junk, *Speculations About a Fourier Series Kicker for the TESLA Damping Ring*, [http://www.hep.uiuc.edu/home/g-gollin/Linear\\_collider/fourier\\_series\\_kicker.pdf](http://www.hep.uiuc.edu/home/g-gollin/Linear_collider/fourier_series_kicker.pdf) (2002).

The kicker's field integral is a function of time, naturally. We use the term "major zero" to refer to the kicker's (zero-valued) field integral when an unkicked bunch passes through the device. Since the bunch spacing in a train is uniform, the time interval between major zeroes is the same as the interval between the kicking impulse and the first major zero.

We have been considering an impulse function of the following form:

$$A(t) = \frac{1}{N^2} \frac{\sin^2\left(\frac{1}{2}\omega_{DR}t\right)}{\sin^2\left(\frac{1}{2}\omega_L t\right)} \cos(\omega_{RF}t) = \frac{1}{N^2} \frac{\sin^2\left(\frac{1}{2}N\omega_L t\right)}{\sin^2\left(\frac{1}{2}\omega_L t\right)} \cos(\Gamma N\omega_L t).$$

An appealing feature of this function is that both the function and its first derivative are zero at all zeroes in the  $\sin^2$  numerator (except for the special case at  $t = 0$ ). This eliminates the residual impulse that might be given to the head (or tail) of a bunch passing through the kicker during a zero in impulse that was not paired with a zero first derivative.

Our kicker simulations suggest that the most significant issue to be addressed is a third-order nonlinear effect. We find that second-order terms at approximately twice the signal frequency (caused by harmonic distortion and intermodulation distortion) could mix with amplifier noise to produce an in-band contribution that cannot be eliminated through adjustment of the initial function generator's program. However, additional studies are needed to reinforce this conclusion.

The kicker will use a pulse compression system that relies on dispersion in a rectangular waveguide transporting power from an amplifier to the kicker's RF structure. Dispersion in the waveguide compresses the amplifier signal: the group and phase velocities for signals propagating down a waveguide with cutoff frequency  $f_{cutoff}$  are

$$v_g = c\sqrt{1 - (f_{cutoff}/f)^2} \quad \text{and} \quad v_\phi = c^2/v_g$$

as shown in Figure 9. This allows an appropriately shaped signal to undergo an evolution of the relative phases of its different frequency components as it travels down the waveguide, effecting the pulse compression.

Much of our recent effort in the lab has involved initial studies of RF properties of (dispersive) waveguides. For short periods of time we are able to borrow space (and instrumentation) in an advanced undergraduate RF lab in the UIUC Dept. of Electrical and Computer Engineering. Our earliest goals are largely pedagogical: we need to familiarize ourselves with standard RF instrumentation and analysis tools in order to work productively at this.

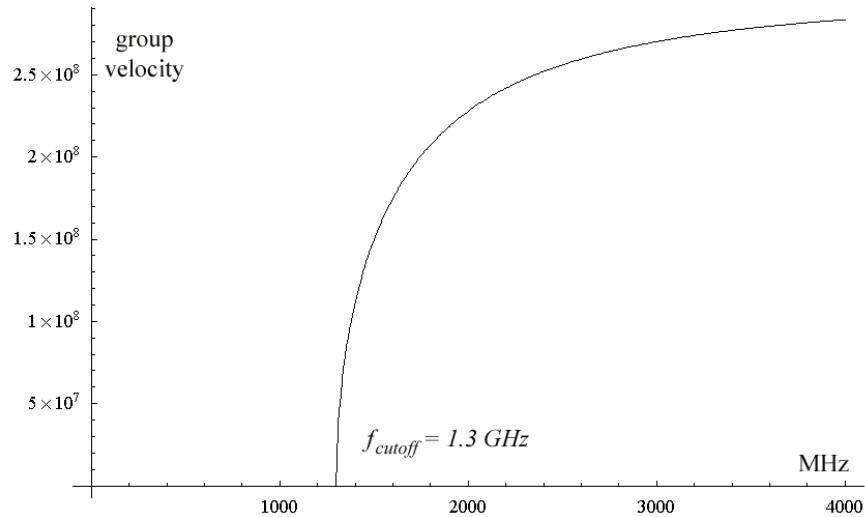


Figure 9: Waveguide group velocity as a function of frequency in the range 0 to 4000 MHz for a 1.3 GHz cutoff frequency waveguide.

We chose to study the behavior of waveguides near  $f_{cutoff}$  as a first project. A rectangular waveguide with transverse widths  $a$  and  $b$  ( $b > a$ ) has  $f_{cutoff} = c/(2b)$ , so our “L band” frequency range corresponds to waveguides that are typically 10 cm wide. This proved convenient in an amusing way: we were able to economize by purchasing inexpensive 4”×3” aluminum downspout, available at a local building supply store for \$9 per ten-foot length, to use as waveguide.

We installed a homemade “launcher” and receiving antenna in the waveguide (downspout!) in hopes of injecting a signal and successfully detecting it at the downstream end, as shown in Figure 10. To our surprise, the very first transmitter/receiver pair we built succeeded in delivering about a quarter of the transmitted power to the terminating resistance attached to the downstream antenna. In addition, a clear cutoff frequency close to the expected value of 1.47 GHz is evident in the measurements of the transfer coefficients (“S parameters”)  $S_{12}$  and  $S_{21}$  that are shown in Figure 11.

Fermilab’s RF group has loaned us several dozen feet of genuine waveguide, and we are now working with that. We intend to confirm that we are able to observe the expected frequency dependence of the waveguide’s group and phase velocities, although our access to the RF lab is reduced due to its use as an instructional facility during the academic year.



Figure 10: Preparation for measurements of the RF properties of 4"×3" aluminum downspout used as L-band waveguide. The dimensions should correspond to a cutoff frequency  $f_{cutoff} = 1.47$  GHz.

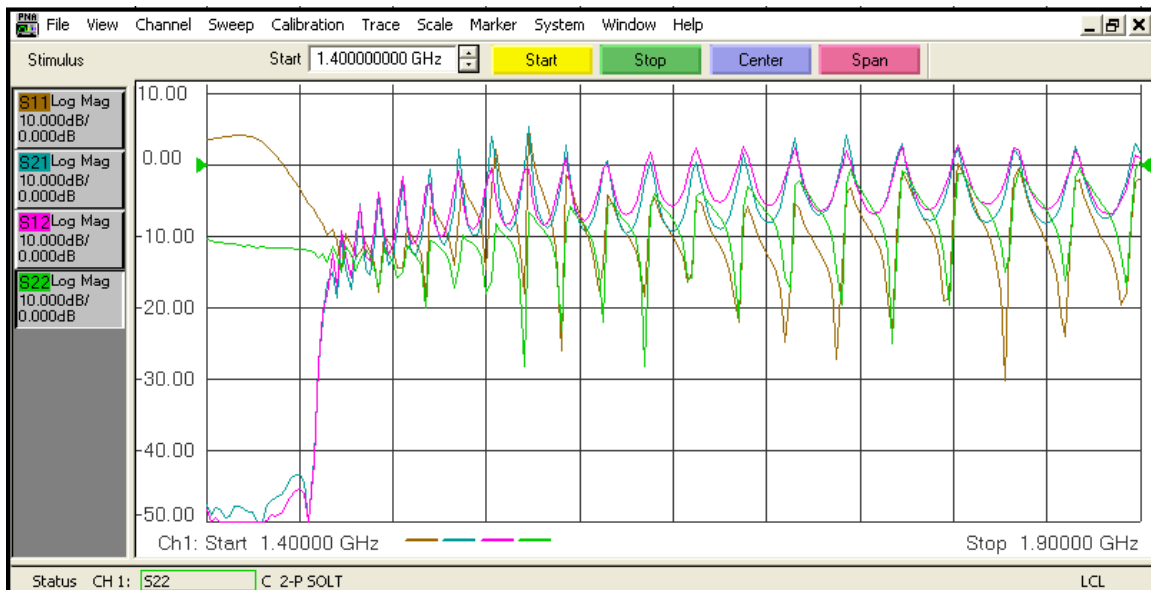


Figure 11: Measurement of “S parameters” for an aluminum downspout used as waveguide. Note the clearly evident cutoff frequency in the vicinity of 1.46 GHz in the parameters S12 (“reverse transfer coefficient”) and S21 (“forward transfer coefficient”).

## Next Year Project Activities and Deliverables

### *Stripline kicker studies using Fermilab's AØ 16 MeV electron beam*

We will use the data on hand to work out the calibration procedures necessary to determine the spatial alignment and nonlinear response of the BPM system. We suspect that there is a significant amount of steering of the beam between the third and fourth BPMs due to unwanted fringe fields from the spectrometer magnet, in spite of the magnetic shielding we had installed to suppress this. We need to understand the size (and stability) of this effect. After we have calibrated our tracking and timing systems we will develop the tools to measure the pulse-to-pulse stability of the kicker impulse amplitude and firing time.

It is likely that our experiences in AØ will lead to a request for modifications to the beamline in order to improve our ability to determine deflections effected by the kicker. It is possible that beam position monitors with higher resolution will be necessary, but we will also need to understand issues associated with stray fields that deflect the beam.

The Cornell group has acquired a FID pulser; in collaboration with them we will use it in place of our slower pulser and determine its stability properties during 2006. Since the FID device is thought to be fast enough to satisfy the ILC requirements on speed and timing stability, an extended test of its amplitude stability and reliability is anticipated.

We expect that the AØ facility will serve as a useful testbed for other fast switches and kicker schemes. Design work on stripline electrode geometry is currently underway at a number of sites and it is likely that we will be able to provide rapid results on the performance of different geometries, although the low beam energy will require an intelligent scaling of voltages to values appropriate for the AØ beam's momentum. In addition, we would like to install a Fourier series kicker module in place of a stripline kicker next year.

### *Fourier series kicker studies and preliminary RF investigations*

We expect to finish our studies of the impact of third-order nonlinear effects on the kicker's performance early in 2006.

The key to building a usable pulse compression system is likely to be the ability to inject signals whose Fourier amplitudes and phases are carefully controlled (and monitored) into the upstream end of a waveguide. We do not have the RF infrastructure necessary at the University of Illinois to perform dedicated studies of this sort. We plan to borrow instrumentation whenever possible, and collaborate with Fermilab's RF group on a series of measurements, but we anticipate requesting support in next year's renewal proposal to obtain a suite of RF instruments to allow us to pursue the work in Urbana.

The RF power range, frequency and bandwidth of a Fourier series kicker suggest the use of a traveling wave tube amplifier (TWTA) rather than a klystron.<sup>6</sup> We imagine driving

---

<sup>6</sup> Ralph Pasquinelli, private communication.

the RF amplifier input with a programmable function generator. The device could be reprogrammed to compensate for drifts in the behavior of the amplifier, waveguide, and RF structure. We would like to begin an investigation of the technical issues associated with the choice of amplifier and function generator.

We have had a number of discussions with Fermilab's RF group and Technical Division about studies of the technical challenges associated with the Fourier series kicker. We plan to collaborate with the lab on the engineering studies necessary to build a prototype module for installation at AØ.

### **Budget justification**

Most of our expenses are associated with salaries for the talented UIUC undergraduate students who work with us (several are listed in the author list of this progress report). Travel to Fermilab and, occasionally, SLAC comprise the bulk of our remaining budgeted expenses. Since ILC work has become the primary focus of Gollin, our funding requirements are expected to increase significantly next year when we submit a renewal proposal that includes our instrumentation needs.

### **UIUC Budget for LCRD 2.22**

Item	FY04	FY05	FY06
Summer + academic year salary, 2 undergraduates (assume 750 hours/year/student, \$6.15/hr)	\$9,225	\$9,225	\$9,225
Indirect costs on undergraduate salaries (53.05%)	\$4,894	\$4,894	\$4,894
Desktop computers for the students	\$6,000	-	-
Periodic student travel to Fermilab during summers	\$1,500	\$1,500	\$1,500
Other travel (one trip to SLAC each year)	\$1,200	\$1,200	\$1,200
Totals	\$22,822	\$16,822	\$16,822