Mastering “Black Magic” with Howard Johnson’s Seminars

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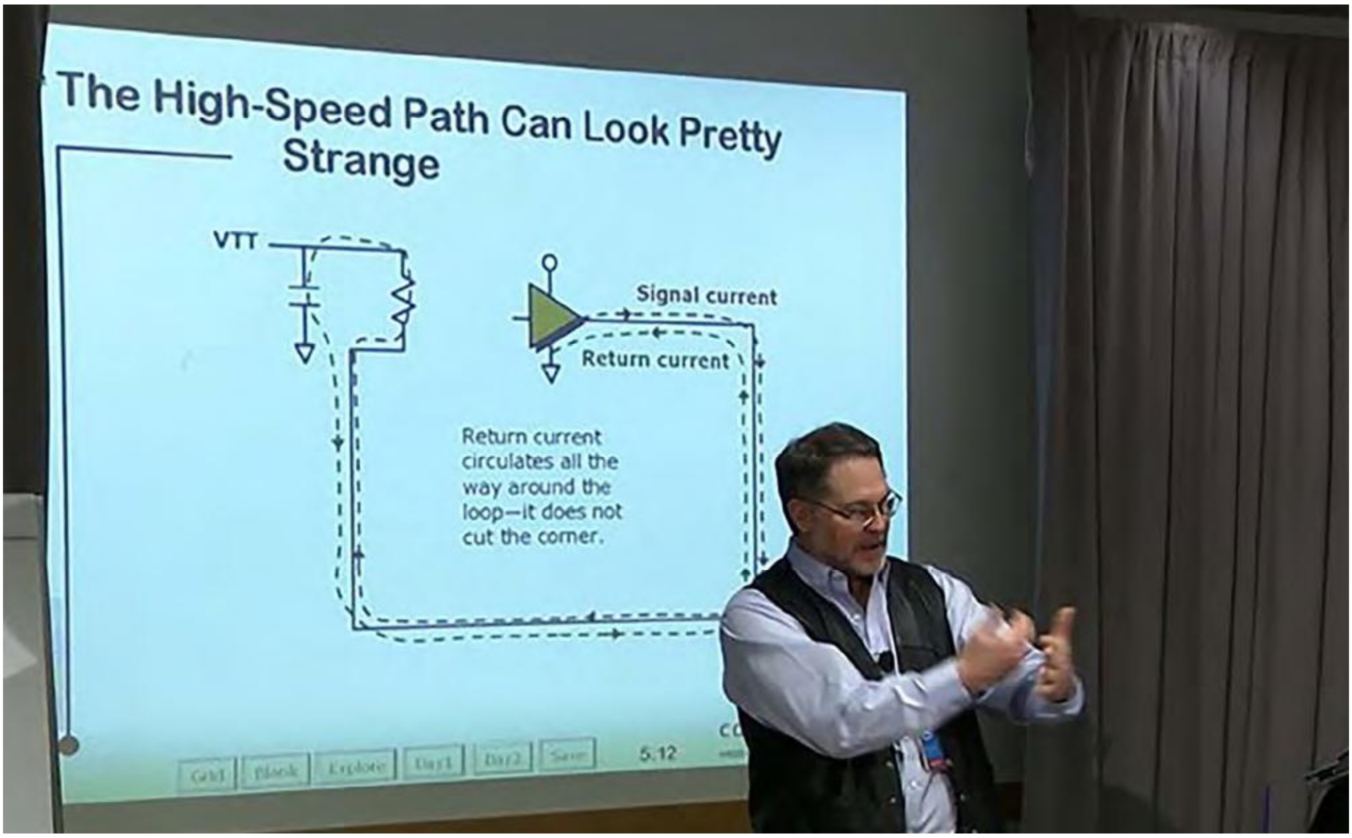
Dr. Howard Johnson, the world’s foremost authority on signal integrity, has recently released his High-Speed Digital Design (HSDD) Collection. This includes professionally recorded seminars that he presented, for more than 20 years, at Oxford University and worldwide and is arguably the most practical and enlightening course on high-speed—black magic—ever delivered. Howard’s unique, explicatory presentation style creates an unforgettable picture of signal propagation by practical example. If you want to gain some of his enthusiasm and master the art of high-speed design, then the collection is a must-have.

I recently had the opportunity to review all three of the seminars in this collection, a total of 36 hours of viewing time. When presented with a selection of three seminars, to watch, I guess it is only natural to want to start with the more advanced topic. But I am glad that I forced myself to start at the beginning to refresh the basics before moving on to the more complex issues. It is amazing how much I either did not know or had simply forgotten over the years. Or maybe I’ve just killed too many brain cells along the way!

I know that during my own courses, there is always one guy at the back who falls asleep. And



The High-Speed Path Can Look Pretty Strange

Return current circulates all the way around the loop—it does not cut the corner.

Figure 1: Dr. Howard Johnson displaying his dynamic teaching style. (All images courtesy of Signal Consulting Inc.)

strangely enough, he is always the one to give bad feedback, probably because he didn't learn anything. But I guarantee that you will be on the edge of your seat throughout Howard's entire seminar series. His dynamic teaching style ensures you feel like you are not just a part of the audience—you are actually participating in the demonstrations. The picture that Howard paints leaves a lasting impression on how electromagnetic fields propagate and how they induce voltages and current (crosstalk) into nearby signals. The following is a section-by-section discussion of the course contents.

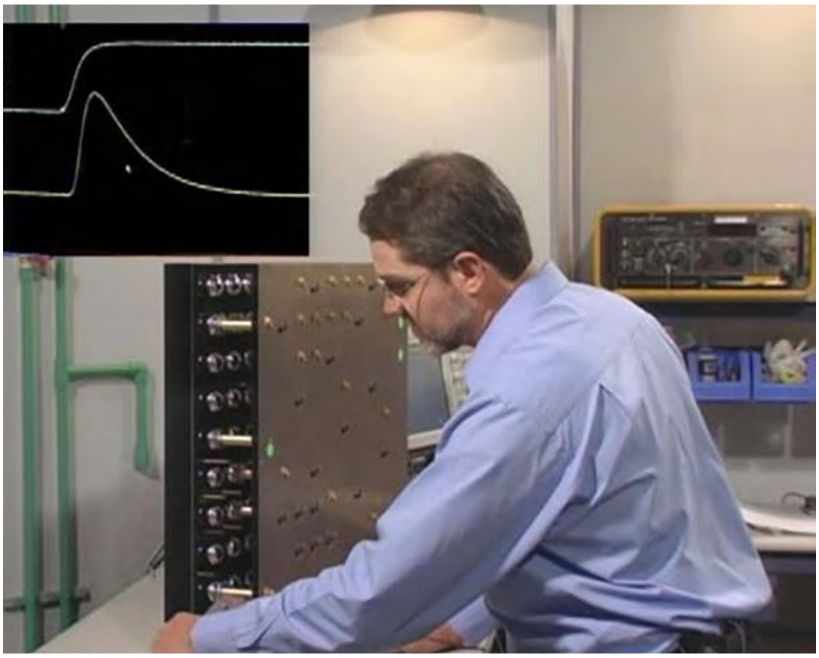


Figure 2: Dr. Johnson measuring crosstalk in his giant scale BGA model.

1. High-Speed Digital Design

Engineers and PCB designers need to understand electromagnetic theory, appreciate how coupling occurs and why energy moves to unintended, sensitive parts of the circuits. A logic schematic diagram masks details crucial to the operation of unintentional signal pathways vital to your understanding of signal performance, crosstalk and EMI. To realize these factors, one must uncover the hidden schematic, operating behind the logic diagram, to reveal the parasitic elements that affect the circuit. These parasitics are invisible to the uninitiated, but become very clear once skillfully explained in detail. You will gain new insight into what really happens in the circuitry.

Also, understanding the frequency band that really matters for digital design is very important. Traditionally, we used 0.35/Tr (where Tr is the rise time in ps) for the upper bandwidth. However, Howard recommends using an upper knee frequency of 0.5/Tr, which forms a crude, but useful, translation between time and frequency domains. So for instance, if the rise time is 500ps, which is typical these days, then the upper bandwidth is actually 1GHz regardless of the clock frequency. Furthermore, the constant improvement in the IC process reduces die size which speeds-up the rising edge. This in turn pushes the knee frequency up, causing signal overshooting and ringing.

Howard also cites the difference between "lumped element" and "distributed systems." In Circuit Theory 101, we are taught using lumped element assumptions where the system delay is much less than the signal rise time. However, Howard points out that when the system delay is much larger than the signal rise time, a more complex distributed analysis is required. This system is characterized by distributed delay and reflections; this is the real world of high-speed design. Here, capacitance draws surge current causing reflections, inductance causes ground (supply) bounce and noise, mutual capacitance causes crosstalk between high impedance circuits and mutual inductance produces crosstalk in connectors especially where the layout is questionable.

I was impressed by the way that Howard addresses bidirectional signal terminations. I have simulated the position of a series resistor on a bidirectional data trace and it doesn't make any difference whether the resistor is placed at either end or in the middle. But, having a resistor at both ends is an elegant solution, as the resistor and input capacitance, of the tri-state load, basically form an AC termination—I would not have thought of that!

2. High-Speed Noise and Grounding

The second seminar in the series focuses on interactions in the real world: electromagnetic compliancy (EMC), which encompasses radiation and susceptibility. Howard looks at a subset of EMC effects, specifically, coupling between circuits within one system, or between large systems in a complex product. He further deliberates on the sort of things that cause intermittent, unreliable behavior of the product in the field and he advises on how to alleviate these issues before they arise.

In Figure 2, Dr. Johnson measures crosstalk in his really cool giant scale BGA model, and looks at supply bounce and ground ball placement on the BGA package. There are also many Signal Integrity Laboratory (SI Lab) experiments embedded in the videos that really help demonstrate the distribution of high-frequency current on reference planes and how crosstalk develops where current loops overlap. And, more importantly, how to avoid crosstalk.

Splitting planes and creating moat and drawbridge constructions are an effective audio frequency solution. But RF coupling (in Figure 3) is quite different, in that it takes place through magnetic and electric fields that can easily propagate through space, going right across a reference plane cut. A sensible solution here is to increase the spacing of coupled devices or add solid shielding. However, you can never completely isolate system components as parasitic capacitance links them whether you like it or not.

For low-impedance circuits, like high-speed computers, most of the issues are related to inductance. Whenever you deviate from a solid reference plane, returning signal current spreads far and wide forming large loop areas and creating radiation. And, mutual inductance connects nearby circuits that don't even touch each other.

If you do a lot of system testing and design verification, in the lab, then this seminar is for you. The second half focuses on system level grounding, connector issues and measurement. Howard also looks at clock related noise issues, the two separate modes of operation—common

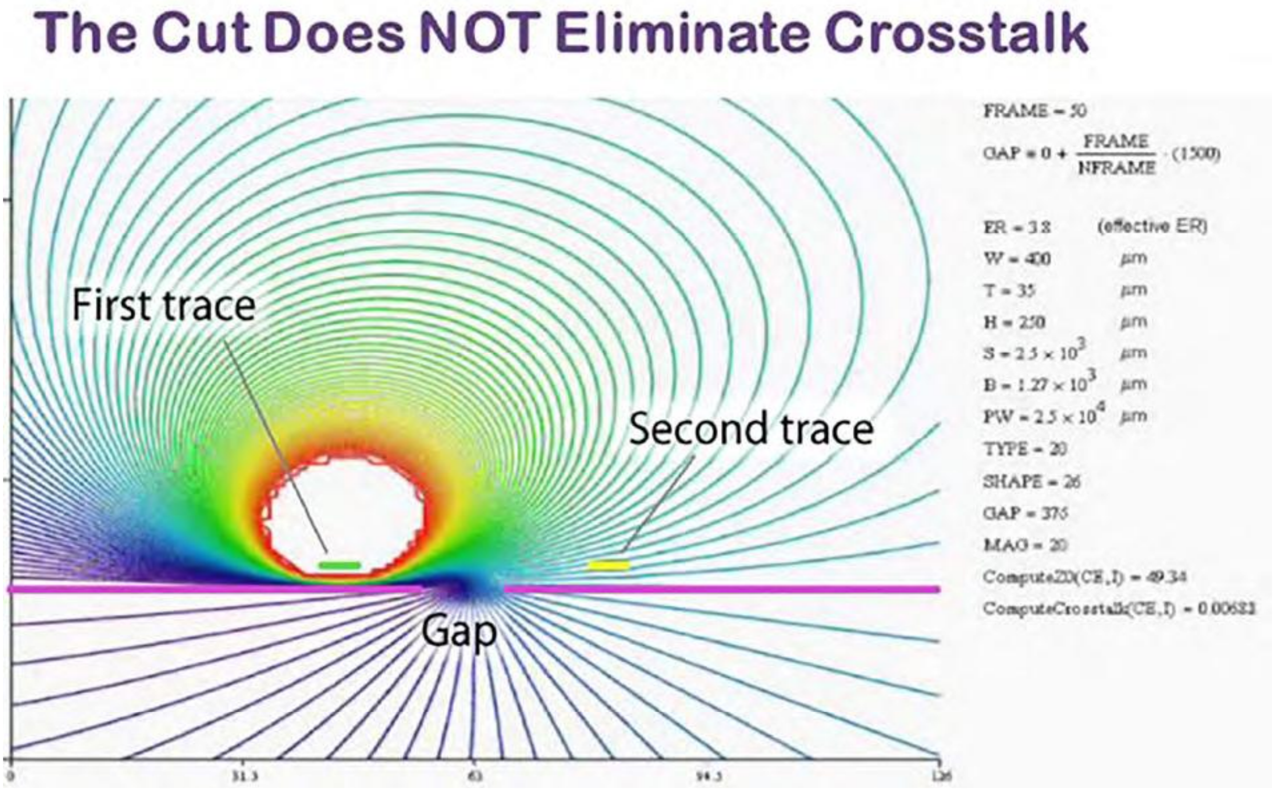


Figure 3: Split planes do not prevent RF coupling.

and differential—plus he discusses clock jitter in detail.

3. Advanced High-Speed Signal Propagation

Now I am ready for the final seminar. I am so glad I did the first two seminars, rather than jumping straight into the advanced level. I am now fully prepared, with all the background knowledge, to move forward with the more complex issues of signal integrity. This seminar is for experienced digital designers, who need to drive their designs to the upper limits of speed and distance. Howard stated, "…without signal integrity tools, you do not know how close you are to that limit. It is our responsibility, as designers, to push the system as close as possible to the edge without ever failing."

As seasoned designers, we are used to looking at circuit parameters in the time domain, like a waveform on an oscilloscope. However, as clock frequencies and edge rates continue to accelerate, one needs to focus instead on scattering parameter (S-parameter) models in the frequency domain in order to effectively evaluate signal propagation in a lossy medium. A two port S-Parameter model of a transmission line is derived in both matrix and equation form. However, cascading networks cannot be evaluated from input to output but rather need to have combined S-parameters for multiple port analysis.

The power spectral density of a digital signal is typically below the knee frequency and if the parasitic impedances are not significant, then digital signals tend to pass undistorted. This is illustrated in Figure 4. Howard prefers to conservatively over-estimate the bandwidth, so that all effects, above the knee frequency, can be safety ignored.

Next is a detailed look at the transmission line model. Howard uses the transverse electro-

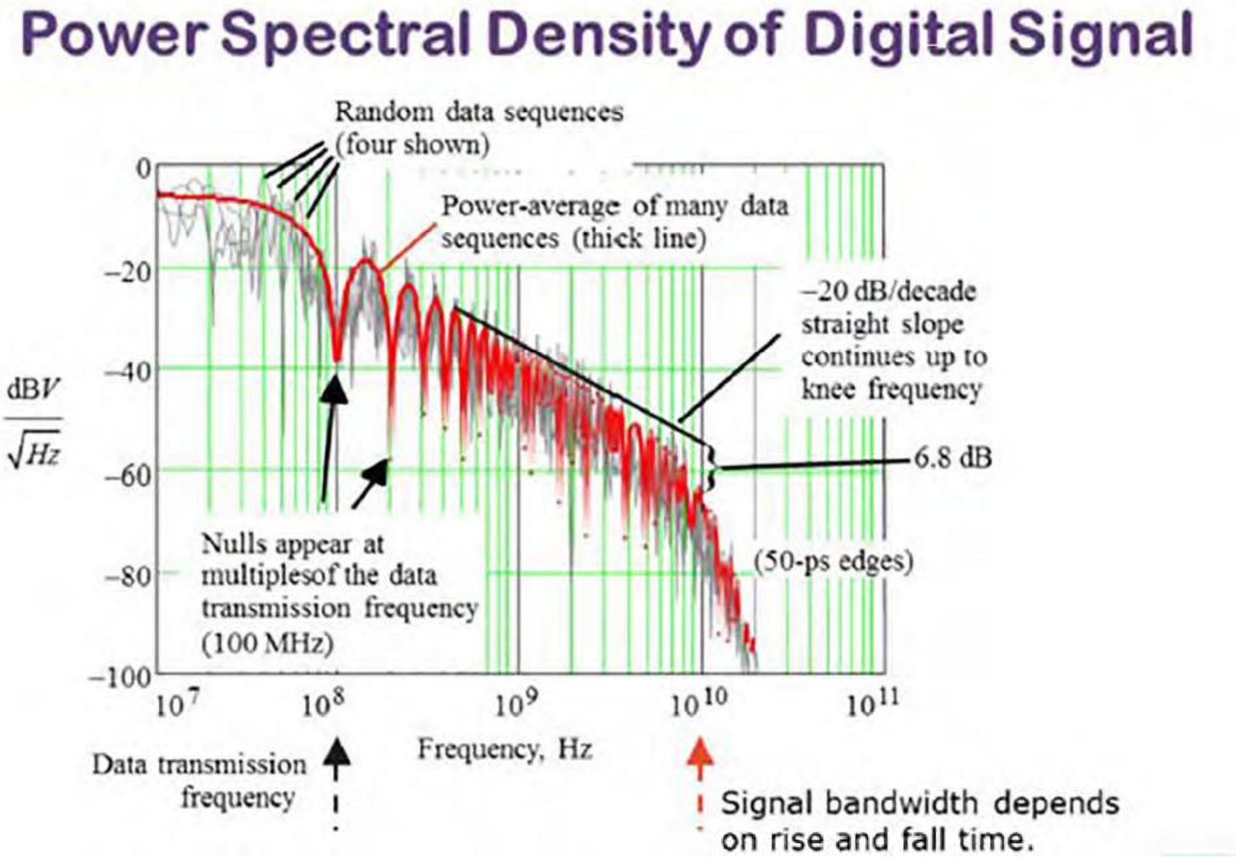


Figure 4: Power spectral density of a digital signal.

magnetic (TEM) mode of propagation, where the electric and magnetic field lines are restricted to the direction of propagation (normal to the direction of propagation), to demonstrate where field lines are prevalent. Transmission lines can be broken down into stages, when the signal and return path are a short fraction of the rise time away from the reference plane.

The returning signal current path is the key to understanding mutual inductive problems in connectors, crosstalk between parallel transmission lines and also EMC. Signal current does not flow down to the end of the signal trace and then return back to the source. But rather, as the signal wave front propagates, the return current builds up simultaneously creating multiple paths back to the source. Howard demonstrates this very effectively with animation showing charged particles as little balls moving in slow motion down a signal trace, while corresponding particles on the returning signal trace move in the opposite direction. It is this type of demonstration that really sticks in the mind and creates a lasting impression. There are also many other animations that clearly demonstrate examples throughout the three seminars.

> “Transmission lines can be broken down into stages, when the signal and return path are a short fraction of the rise time away from the reference plane.”

A discussion of skin depth, where current flows only in a shallow band at high frequencies, and dielectric losses that need to be considered at high frequencies, follows. A non-uniform distribution of current, around the periphery of a conductor, creates a non-concentric field. At high frequencies, magnetic lines of force will not penetrate a conductor but rather flow tangential to the conducting surface. The trick is to ensure that the radiated field lines do not flow between the victim signal trace and reference planes, inducing current and hence crosstalk. Howard also points out that dielectric loss is not a function of the conductor geometry but depends on the loss tangent of the surrounding materials. This is why a low loss dielectric material (Df = 0.002) is more effective, at high frequencies, compared to standard FR-4 (Df = 0.02). Dielectric loss is also frequency dependent, so the maximum frequency of operation is also significant.

Finally, the section I have been waiting for: PCB traces, connectors, vias and differential signaling. Microstrip and stripline stackup configurations are discussed, in detail, with the effects of surface roughness, nickel plating and solder masks. This necessitates the use of a 2D field solver such as the ICD Stackup Planner.

The time-space diagrams of transmission line reflections are very enlightening. This is a simple way of analyzing reflections from downstream loads on the transmission line. A load at the end or multiple loads, along a multi-drop line, look like capacitors (IC input capacitance). These delay the rising edge and reflect back down the transmission line as near-end crosstalk (NEXT), creating "potholes" in the signal. Howard has a unique solution to this crosstalk by deliberately creating an equal and opposite reflection to neutralize the pothole. This technique is ideal for the fly-by routing of multidrop loads. I will definitely implement this strategy on my next DDR3/4 design.

Types of PCB connectors and the use of proper grounding, to alleviate high inductance and EMI, are also discussed. Vias are basically a type of connector that transfers a signal from layer-to-layer in a multilayer PCB. So, ground stitching vias need to be utilized in order to reduce loop inductance. Removal of unused inner layer via pads reduces capacitance. Dangling vias create reflections above 1GHz but can be improved by back-drilling, using truncated vias or special antipad clearances. Howard's approach for differential vias is unique.

Differential signaling also has its challenges and both differential-mode and common-mode noise are discussed in detail. Reducing common mode noise is the key to good differential design. There are also special issues with crosstalk, on differential signals, that can easily be avoided. Solutions for breaking a pair, termination, change of reference planes, trace skew and DC blocking layout techniques are described in detail.

Finally, one of the most important aspects of HSDD is revealed: clock distribution. All you ever wanted to know about effectively routing clocks, loaded delay, the forward crosstalk (FEXT) of serpentine traces, daisy-chain routing of multiple loads and the effects of jitter on clock eyes. Dr. Johnson’s collection is a must-see for all digital design engineers and PCB designers who need to understand electromagnetic theory, appreciate how coupling occurs and why energy moves to unintended, sensitive parts of the circuits. And, more importantly, how to prevent electromagnetic coupling.

I read that when Albert Einstein was teaching at Princeton, he prepared an examination paper and handed it to his assistant. The assistant queried, “Albert, isn’t this the same exam you gave this class last year?” Einstein replied, “Yes it is. The questions are the same, but the answers have changed!”

Digital designers need to keep up with the fast changing pace of technology. For all the latest solutions, to complex Signal Integrity issues, I recommend the High-Speed Digital Design Collection. **PCBDESIGN**

References

1. Dr. Howard Johnson, Signal Consulting: High-Speed Digital Design Collection

2. Howard Johnson, Martin Graham: High-Speed Digital Design – A Handbook of Black Magic

3. Howard Johnson, Martin Graham: High-Speed Signal Propagation – Advanced Black Magic

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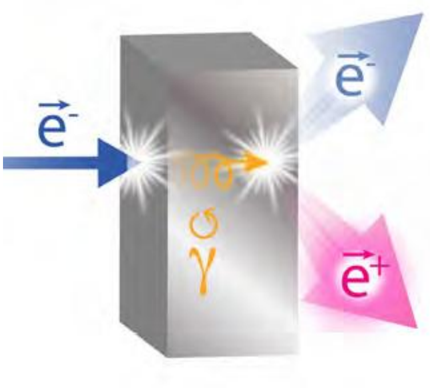
Spinning Electrons Yield Positrons for Research



Using the Continuous Electron Beam Accelerator Facility (CEBAF) at the Department of Energy’s Jefferson Lab, a team of researchers has, for the first time, demonstrated a new technique for producing polarized positrons.

Jefferson Lab Injector Scientist Joe Grames says the idea for the method grew out of the many advances that have been made in understanding and controlling the electron beams used for research in CEBAF.

“We have a lot of experience here at Jefferson Lab in operating a world-leading electron accelerator,” Grames said. “We are constantly improving the electron beam for the experiments, pushing the limits of what we can get the electrons to do.”

Grames and his colleagues would like to take that finesse a step further and transform CEBAF’s well-controlled polarized electron beams into well-controlled beams of polarized positrons to offer researchers at Jefferson Lab an additional probe of nuclear matter. They named the endeavor the Polarized Electrons for Polarized Positrons experiment, or PEPPo.

Throughout the process, the polarization of the original electron beam is passed along. The researchers use a magnet to siphon the positrons away from the other particles and direct them into a detector system that measures their energy and polarization.

“We showed that there’s a very efficient transfer of polarization from electrons to the positrons,” said Grames.