The Proposed Doppler Electron Velocimeter and the Need for Nanoscale Dynamics

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Importance of Nanoscale Dynamics

As engineering challenges grow in the ever-shrinking world of nano-design, methods of making dynamic measurements of nano-materials and systems become more important. The Doppler electron velocimeter (DEV) is a new measurement concept motivated by the increasing importance of nano-dynamics. Nano-dynamics is defined in this context as any phenomenon that causes a dynamically changing phase in an electron beam, and includes traditional mechanical motion, as well as additional phenomena including changing magnetic and electric fields. The DEV is only a theoretical device at this point. This article highlights the importance of pursuing nano-dynamics and presents a case that the electron microscope and its associated optics are a viable test bed to develop this new measurement tool.

As background, microelectromechanical systems (MEMS), a very active area of research at Sandia National Laboratories, has benefited greatly from investigating the dynamic characteristics of MEMS devices. This includes investigations of both fundamental physics interactions, such as air damping, and the more immediate needs of qualifying and designing current devices. An example of this application is an RF-MEMS switch design, where accounting for the dynamic motion is critical to optimizing both the system life and the switching speed. Figure 1 shows the operating shape at 47 kHz and the frequency response function of the device from 0 to 50 kHz. From this information, not only are the resonant frequencies and mode shapes obtained, but the quality factor, or damping, can also be measured. These measurements were made using a laser Doppler velocimeter (LDV)—the current state of the art for making dynamic MEMS measurements, at least at the micron scale.

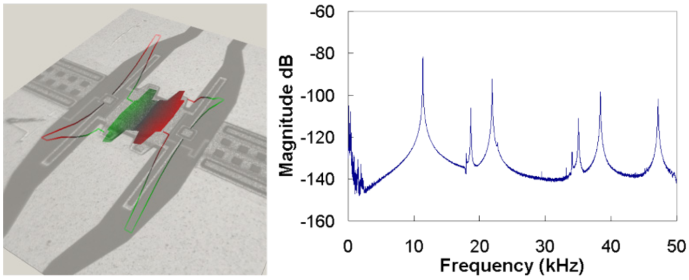


Figure 1. MEMS velocity profile showing operating shape and quality factor (Photo and data courtesy David Epp – Sandia National Laboratories).

Possible Applications of the DEV

What are some applications for DEV? One area of intense interest is in measuring the internal dissipation of nano-devices, usually cantilever beams at size scales in the nanometers. Internal dissipation is almost impossible to measure currently, and it is the defining characteristic for using the nano-cantilevers in commercial devices such as electronic filtering, resonant sensing apparatus, the creation of nano-clocks, and quantum information processing. Internal dissipation, related to the quality factor, is measured by exciting the structure and determining the frequency response at resonance. The sharpness of the peak is proportional to the *q*. See Figure 1 as an example. Quality factor measurements are routinely done with a laser velocimeter, but only when the structures are larger than 500 nm. Microscopists are also doing mechanical testing of nanostructures using TEMs, say, for measuring the material's modulus. Similar information could be obtained via dynamic measurements as a secondary check on the accuracy. Other interesting experiments exist in the regime where a DEV would be required.

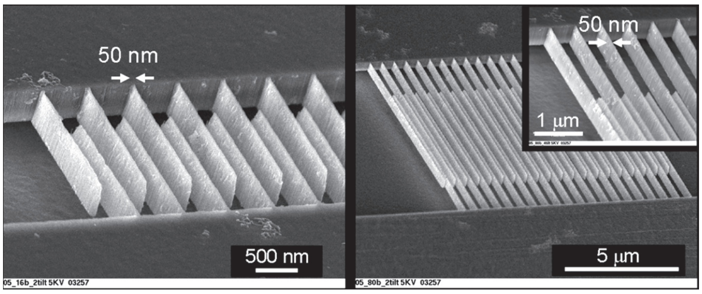


Figure 2. Nanoscale beams too small for detection with a laser based velocity measurement (Image courtesy John Sullivan of Sandia National Laboratories).

LDV Problems at Small Scales

The LDV has been a key research tool in MEMS investigations. The standard LDV has been optimized and integrated with an optical microscope to allow the insertion of the probe beam for making MEMS measurements. These interferometers provide extremely accurate velocity and displacement measurements that are now routinely used for MEMS diagnostics and design work. They work on the simple principle of the Doppler shifting of the light wavelength. The probe beam is one leg of a traditional Mach-Zehnder interferometer, where the object leg of the interferometer is routed through the microscope to the sample and then mixed with a reference beam to create a heterodyned Doppler signal. The frequency signal is then decoded to yield velocity, or alternately, the interference fringes are counted to give displacement.

However, as the MEMS world increasingly pushes the envelope of smaller and smaller designs, the standard laser measurement system is useless at the sub-micron scales. This limitation is caused by diffraction limitations of the probe laser light beam dictated by the wave nature of the light. Even with the best optics (highest numerical apertures), laser systems are diffraction limited to a spot size of approximately one-half micron. The spot size is fundamentally controlled by the wavelength of the energy traveling through the optics. This is applicable whether the optics are glass as traditionally used with light, or electron optics when considering electron microscopes. The shorter electron wavelengths are the key advantage of using an electron microscope. Even with very modest accelerating potentials, extremely short wavelength electron beams can be produced.

For example, in Figure 3, I have created a comparison between the spot size and wavelength of typical He-Ne laser light, with a wavelength of 632 nm and a low-energy electron beam accelerated with a 1 kV potential and having a wavelength of 0.04 nm. The large disparity between the probe spot sizes and the wavelengths is obvious. The black background on the right is the electron-wave oscillation, with approximately 15,800 cycles in a single cycle of the light. As the object size decreases, the spot size becomes the critical parameter. When the measurement probe becomes larger than the structure, the velocity becomes ambiguous or unable to

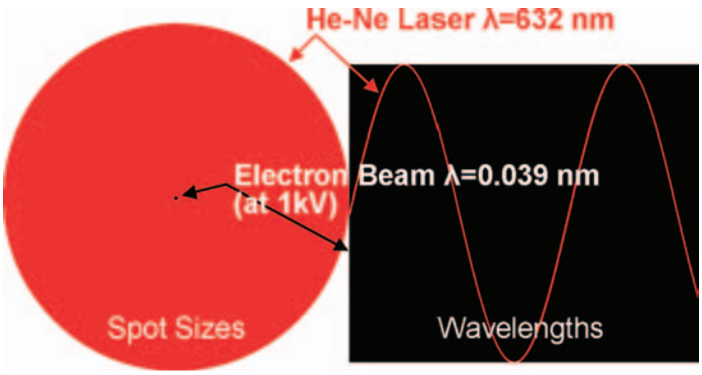


Figure 3. Comparison of spot size and wavelength between electron beam and laser light.

be measured. In fact, some MEMS devices are already too small to be measured with laser systems. The potential for having extremely small probe beams is one great advantage of using electron beams rather than laser light.

Electron Holography Opens the Door

The broad field of optical holography was started by Gabor, who began his research using early electron microscopes. His motivation was to increase the instrument's spatial resolution by cancelling out spherical aberrations using holography [1]. He subsequently went on to do optical experiments and demonstrated the concept very successfully with light and photographic film. The DEV moves in the opposite direction, using an optical analogy of Doppler light and extending it into the electron beam realm. This starting point for holography is of more than historical interest; it also emphasizes the main drive of electron holography and electron optics over the last 50 years—namely, increasing the spatial resolution of the images. This emphasis in some ways allowed the application of electron interference to be overlooked for many years. Recently, researchers have begun using electron microscopes optimized for interferometry to make important physical measurements in areas such as magnetic field strength and superconductivity.

The electron microscope, which inspired Gabor, has progressed significantly since the 1950s. Commercial transmission electron microscope systems are available with coherent sources of good brightness and are even optimized specifically for holography (Hitachi HF-2000). Important for the development of the DEV is that at this point, electron analogs for nearly all the traditional optical components required for holography have been demonstrated, including beam-splitters, mirrors, and prisms. Additionally, following in the tradition of the classical interferometric experiments of Fizeau, Michelson, Rayleigh, and Fabry and Perot in the optical domain, researchers have conducted similar experiments using electron microscopes, including the traditional interferometric arrangements of Young's double hole, the Fresnel biprism, and Mach-Zehnder and Michelson interferometers. The standard arrangement used in a transmission electron microscope is a Möllenstedt biprism, which is analogous to an optical beam splitting device that creates two coherent images of a single source. A number of good review papers and books cover in more detail the general concepts of electron holography, including Tonomura [2], Missiroli [3], and Völkl [4].

How Would the DEV Work?

Louis de Broglie in his 1924 doctoral thesis posited that if light waves may be viewed as particles, with the recently developed idea of the photon, maybe particles should also be viewed as waves. His revolutionary concept resulted in the well-known equation relating momentum (p) and Plank's constant (h) to the wavelength of the particle (λ):

$$p = \frac{h}{\lambda}.$$

This is extended to define an electron wavelength in a microscope with an accelerating potential of U in volts as:

$$\lambda = \frac{1.226}{\sqrt{U\left(1 + 0.9788 \times 10^{-6} U\right)}} \text{ (nm).}$$

As mentioned previously, the great strength of using electrons as the probe beam is the extremely short wavelength, even with relatively modest accelerating potentials. Add to this the well-developed electron optics, sources, and detector components, and one can see why the electron microscope is an ideal platform on which to build a nanoscale dynamic measurement device.

As discovered by de Broglie, the electron can now be described as a wave or, more accurately, a wave packet, which includes the concepts of coherence to be discussed later. Along with this wave behavior is the ability to interfere and create interference fringes, analogous to light. These analogies to optical behavior are important to the argument for creating the DEV.

Fringe-Counting Is Doppler

That electron holography works has been repeatedly demonstrated with TEMs. The bigger question for this article is whether using Doppler shifting of electrons is practical. One useful way of viewing Doppler measurements is by the simpler concept of fringe counting. Consider a beam splitting interferometer, which creates a series of fringes on the detector that vary with the motion (or other property) of the phase shifting object in its path. If the phase shifts dynamically, the fringes will move as a function of time. Moving

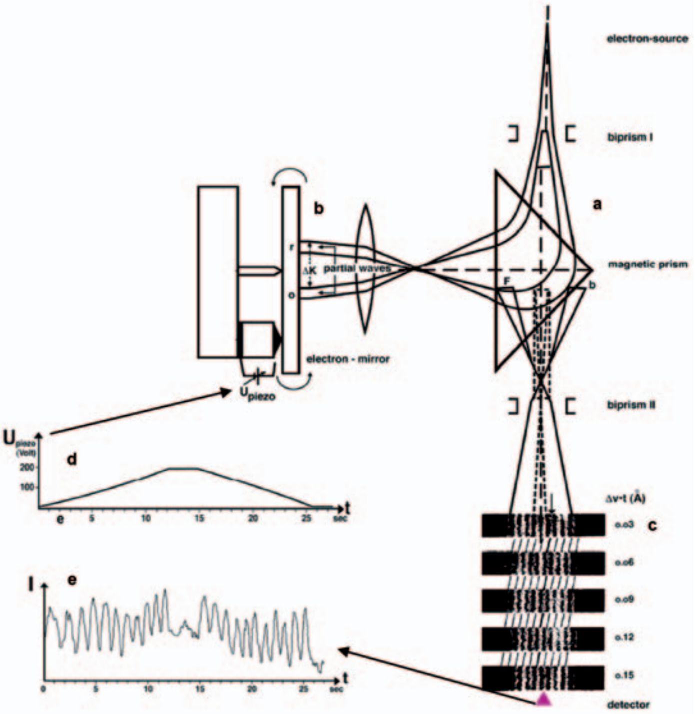
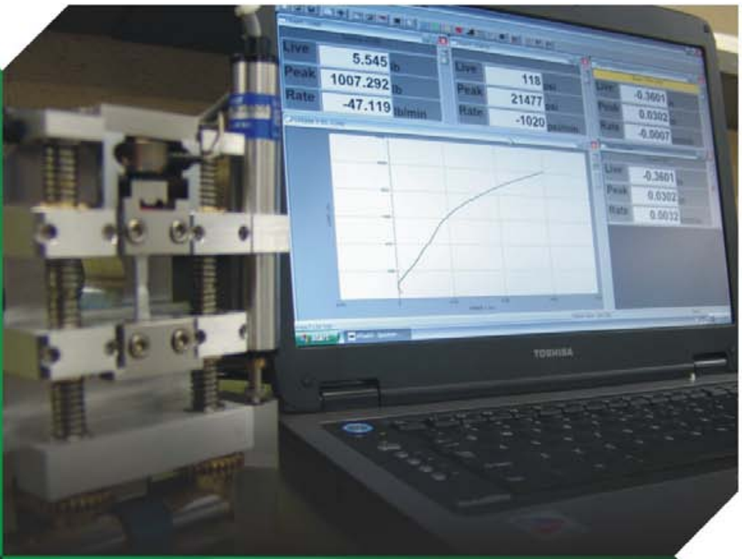
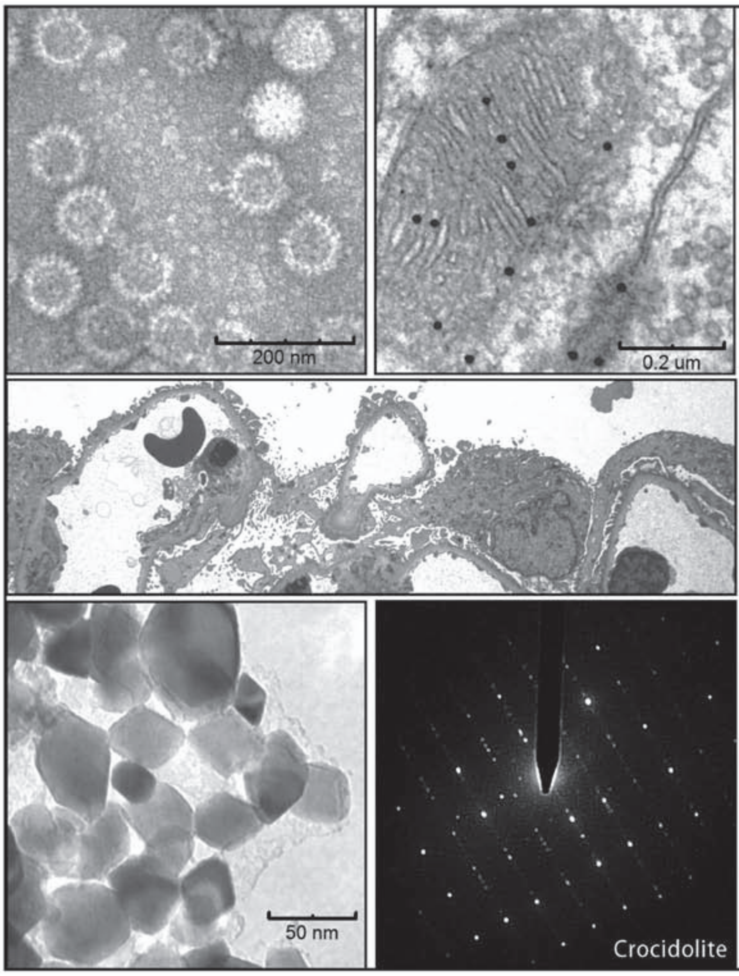
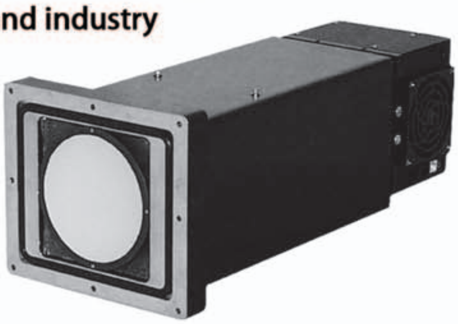


Figure 4. Illustrations from Möllenstedt and Lichte paper [6]. a) Michelson interferometer, b) electron mirror, c) moving fringes, d) voltage applied to piezo, and e) Doppler beat because of velocity of mirror.




200 nm
0.2 um
50 nm
Crocidolite



electron interference fringes have been seen at video-rates by a number of researchers, and dynamic magnetic fields have been measured that temporally vary the phase shift of the electron object beam [5]. The important concept is that moving fringes are equivalent to Doppler shifting. In mathematical terms, the Doppler measurement of the frequency shift is the instantaneous derivative of a temporal phase change. In other words, counting fringes per second is equivalent to the Doppler frequency. Therefore, researchers who have observed moving fringes are making Doppler measurements! This was first demonstrated in 1978 by Möllenstedt and Lichte.

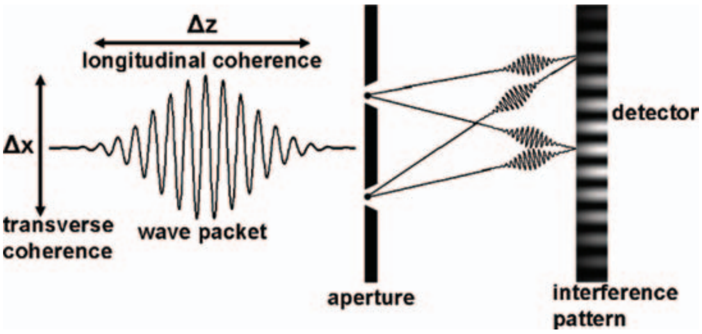


Figure 5. Young's double slit experiment illustrating coherence limits on fringe formation.

Electron Doppler Demonstrated

The first demonstration of Doppler shifted electrons was by Möllenstedt and Lichte [6]. They used two biprisms and a rotating electron mirror to impart a Doppler shift to the object and reference beams of a Michelson interferometer setup. The fringes formed by the biprism move as the object rotates, causing a time-varying current to be measured. This time varying intensity is the heterodyned Doppler frequency that is proportional to the mirror velocity. This is demonstrated in a figure reproduced from their paper shown in Figure 4. That the concept has been demonstrated is important. However, it should be noted that the velocity measured was extremely small, some picometers/second. For practical measurements, the dynamic velocity range must be greatly increased. Increasing the useful dynamic range has important implications for the design of a DEV, including source coherence, maximum allowable Doppler shifts, and beam current. These three inter-related topics are the greatest challenge to creating a practical DEV.

Challenges for Creating a DEV

Coherence

Coherence can be thought of as the relationship of the wavefront in a given wave packet and has two components, both of which are important for a working DEV. They are transverse and longitudinal coherence (often called spatial and temporal). Young's double-slit experiment, illustrated in Figure 5, is useful for giving a physical feel for how the coherence limits affect fringe formation. For successful fringe formation, the transverse coherence must be wide enough to cover both holes, and the longitudinal coherence must be long enough to overlap after traveling different distances from each hole to a point on the screen where they interfere.

The longitudinal coherence is determined by the energy spread of the beam, Δ*E*. A typical source with a spread of 1 eV results in a coherence length of 680 nm. Experiments have confirmed the longitudinal coherence calculations. The transverse coherence depends upon the uniformity of the phase front at some point in space. The transverse coherence is inversely related to the source tip size by the van Cittert-Zernicke theorem. Most modern sources have extremely small tips and are capable of coherently filling the entire aperture of a modern electron microscope. As discussed, the two key parameters for a good source for holography are the energy spread and the tip size. Table 1 gives a survey of available sources and their related properties as they pertain to the DEV.

Fringe Formation Time and Beam Current

Those practitioners with experience in creating an electron hologram know that the typical exposure times are in seconds, if not minutes. This obviously is not acceptable if one wants to image fast-moving fringes or, equivalently, the Doppler frequency. The key to decreasing the detection time is in increasing the beam current. One potential advantage of the DEV is that it is not an imaging system, but a point measurement, so more current is theoretically available for detection. Of course, it may not be as simple as creating a single high-current beam, as there are two potential drawbacks, including sample damage and an unknown effect of beam current on the coherence. A related concept is detector speed. Up to this point, detection speed has been unimportant in electron microscopy because spatial resolution has been the driving force. Therefore, there has been little effort in creating high-bandwidth (MHz or GHz) electron detectors. Essentially, what is needed is an electron equivalent to a fast photodiode. These two concerns will be active areas of research as this project moves forward.

Energy Arguments – A Case Against the DEV

Some researchers have postulated that moving fringes and therefore Doppler shifting of electrons are impossible because of the beam energy shift caused by the sample and potential incoherence of the electrons [7]. I, of course, take the counter view based on two arguments: first, moving fringes have been detected and second, even incoherent sources are able to interfere to create fringe patterns. The energy shift argument, however, is an important one and should not be dismissed lightly. The primary aspect to consider is the scale of the energy shift. Typically, energy shifts in electron microscopy are thought of in terms of inelastic scattering where 1 to 2 keV shifts are typical. For Doppler considerations, the shifts are typically much smaller and are defined by the equation:

$$\delta E = \left| E_0 - E_R \right| = h\,\delta f < \frac{h}{t},$$

where E_O is the object beam energy and E_R is the reference beam energy, δE is the energy shift, δf is the Doppler frequency shift of the

Table 1. Available sources for DEV.

Electron Beam Sources	Required Vacuum (Torr)	Virtual Source Diameter (μm)	Energy Width (eV)	Acceleration Voltage (kV)	Measured Brightness (A cm^{-2} sr^{-1})	Current Density at Specimen (A cm^{-2})
Heated Field Emission	10^{-8}-10^{-9}	0.1	0.8	100	10^{7}-10^{8}	20
RT Field Emission	10^{-10}	0.002	0.28	100	2×10^{9}	4000
Hair-Pin Cathode	10^{-5}	30	0.8	100	5×10^{5}	1
Tungsten (W) Cathode	10^{-6}	10 – 50	1-2	100	1 to 5×10^{5}	3
LaB_6 Cathode	10^{-6}	5 – 10	1	75	7×10^{6}	14

moving fringes, and *t* is the sensor detection time. These quantities are illustrated in Figure 6. This equation shows that for even modest energy shifts, the record time moves into the millisecond range, again indicating the need for high beam currents and fast detectors. Interestingly, the energy shift demonstrated by Möllenstedt was $4e^{-15}$, which resulted in a record time of 1 s, allowing a researcher to use a simple phosphor screen and a photodiode. As a possibility, newer faster phosphors are available with nanosecond response times that may be effective in increasing the allowable energy shift. The energy argument is summarized graphically in Figure 6, where for successful fringe formation, the object and reference beam energies must still overlap for the electron to interfere [8]. That is, as long as the energy shift of the sample, δE, is less than the energy spread of the source, ΔE, fringes will be formed, and Doppler measurements could be made.

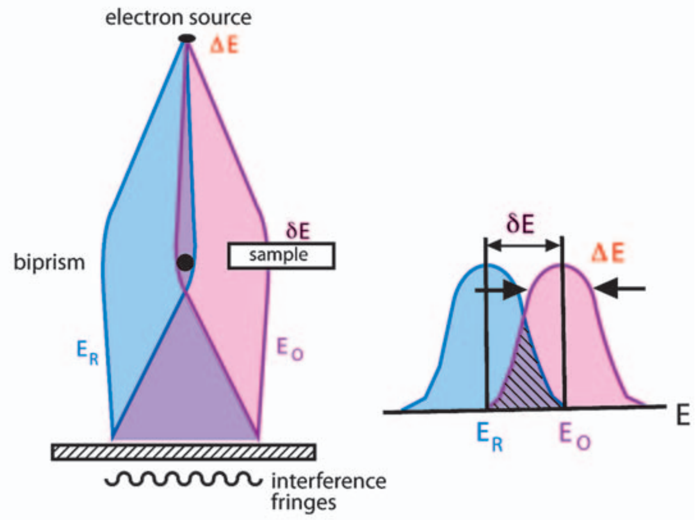


Figure 6. Möllenstedt biprism with phase shifting object in one leg of the interferometer [9].

To answer the objection regarding a lack of coherence in the electrons at the point of detection, I will cite the analogous situation in light interference and a recent experiment using electrons. Incoherent interference is demonstrated in the optical analogy by the fact that incoherent sources can and do interfere and have been used to make Doppler measurements by this researcher [10]. Similarly, using a Lau-Talbot interferometer arrangement and an incoherent electron source, interference fringes have been formed by means of nanometer-scaled gratings [11].

Conclusions

It is important to remember that this is a theoretical device at this point; however, the arguments presented, at least to the author, seem to indicate that a DEV is possible, with one important development, namely, faster detectors. Related is the issue of beam current, and the effects on coherence and interference that may result from increasing the current to reduce detection time. Ongoing research is being conducted to more accurately quantify the required beam currents and detector technology to aid in determining a path forward for creating a practical nano-dynamics measurement tool. This is driven by practical needs including, current and emerging applications where dynamic measurements would be useful, such as, nano-machine design and basic physics research like internal damping. Furthermore, setting up a robust electron interferometer opens up the possibility of doing basic quantum mechanical research using electrons. While this article approached the topic from the idea of using electrons, there is no reason that particles could not also be used. ■

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