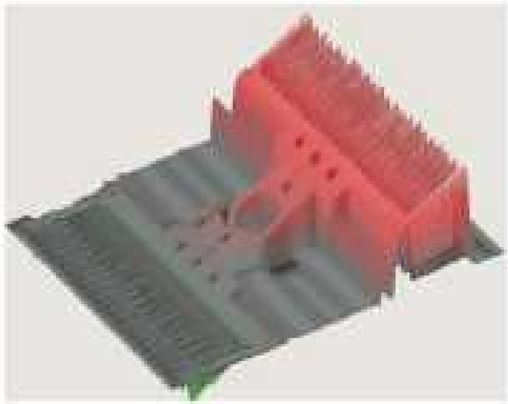
Doppler electron velocimeter—practical considerations for a useful tool

SAND2008-4072C

Can this TEM…



…do this?

SEM Annual Conference June 2-6, 2008

Phillip L. Reu

Senior Member Technical Staff

National Nuclear Security Administration

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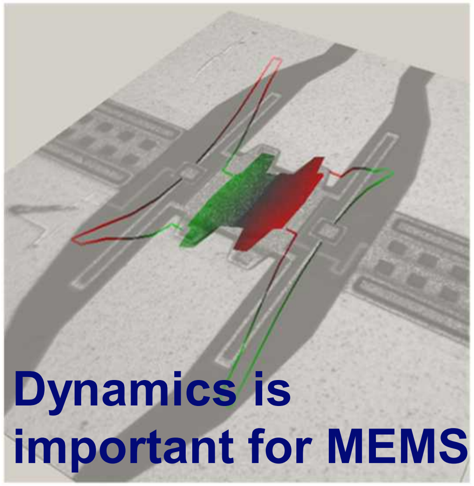
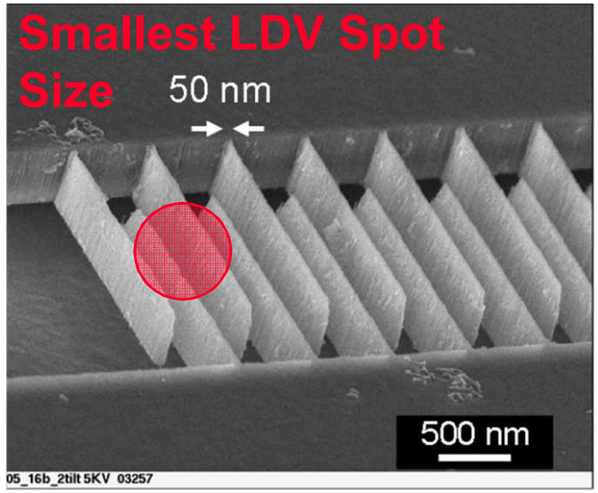
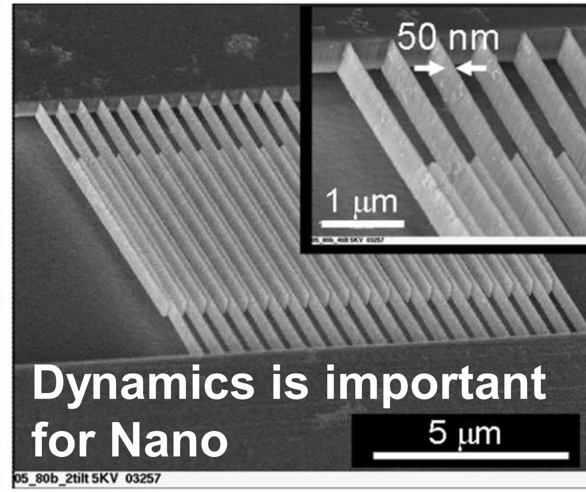
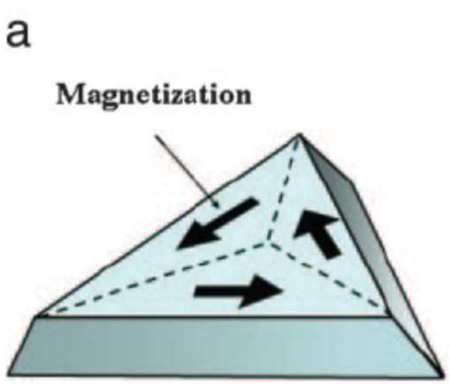
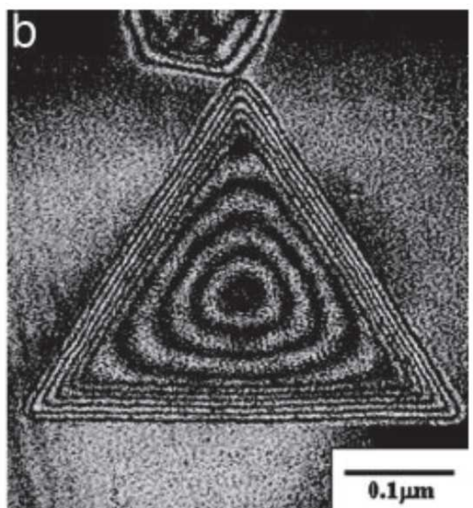
Nanodynamics, an important future discipline!











Magnetic field measurement

Electric field measurement

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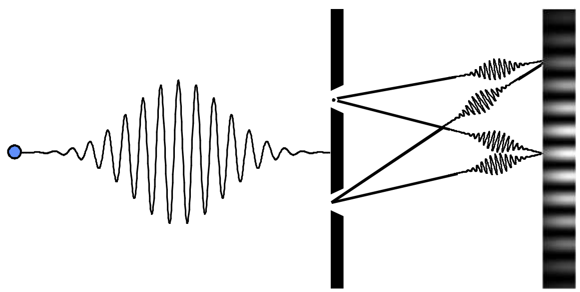
Proceedings of the National Academy of Sciences in the United States of America, Sept. 6 2005, Akira Tonomura

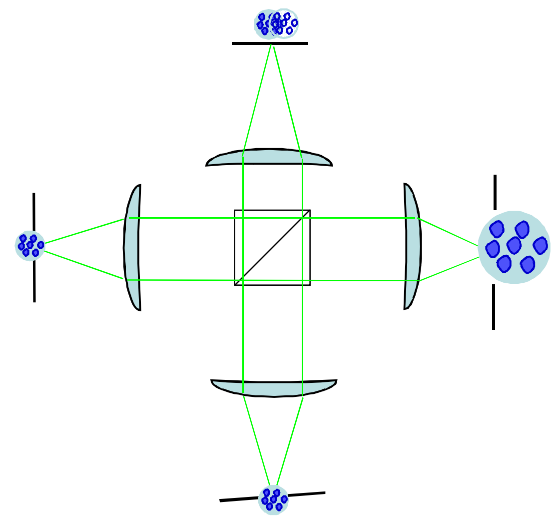
Rev. of Modern Phys., July 1987, A. Tonomura

Can a practical electron velocimeter be created?

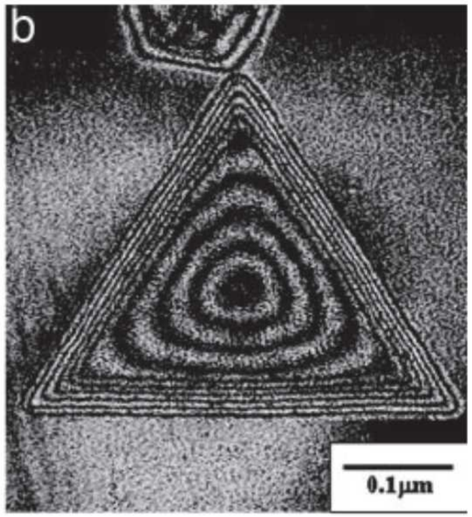
Coherence and interference



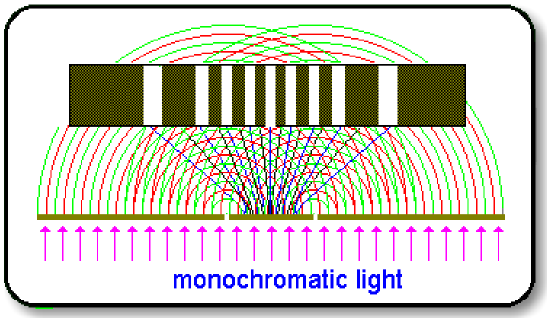
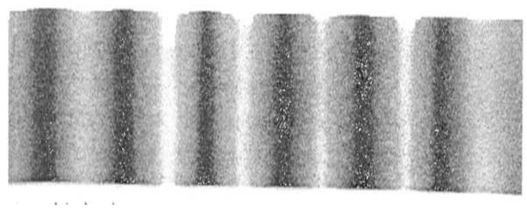
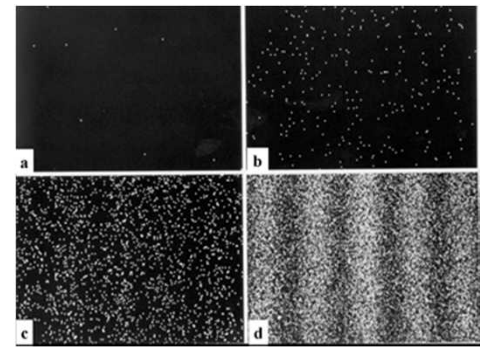
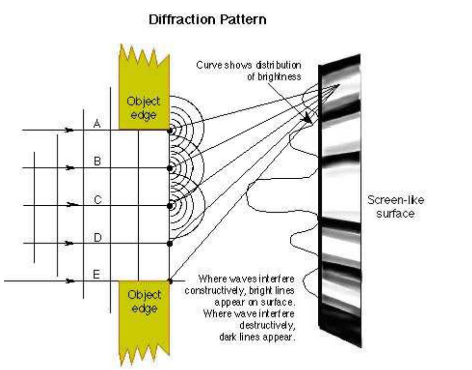
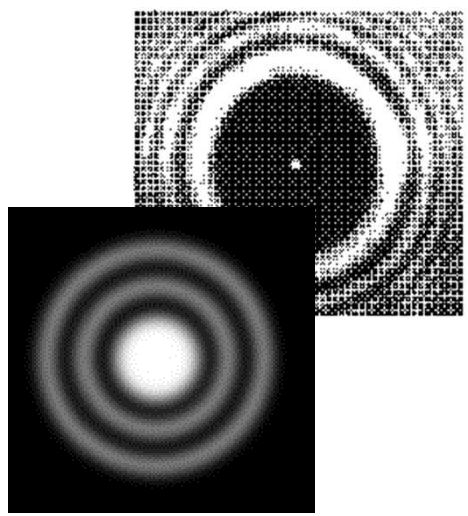
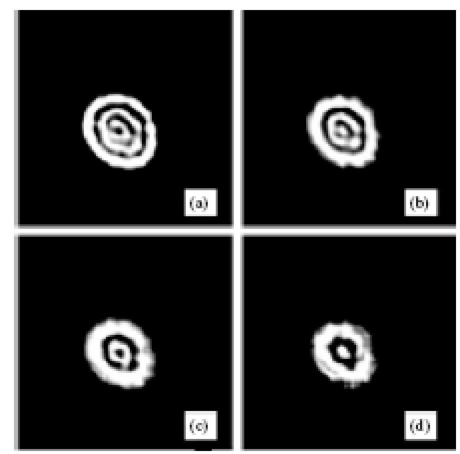
Overcoming Beam Limitations



What can be measured?



Mutatis mutandis – Photons and electrons behave nearly the same

	Schematic	Photons (Boson)	Electrons (Fermion)
Interference		 http://www.physchem.co.za/Light/Diffraction.htm	 http://www.hqrd.hitachi.co.jp/em/emgif/fig2.gif
Diffraction	 http://planetquest.jpl.nasa.gov/technology/diffraction.cfm	 http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/frestr.html http://www.atmsite.org/contrib/Poulson/faq/airydisk.JPG	 Eur. J. Phys. **26** (2005) 481–489

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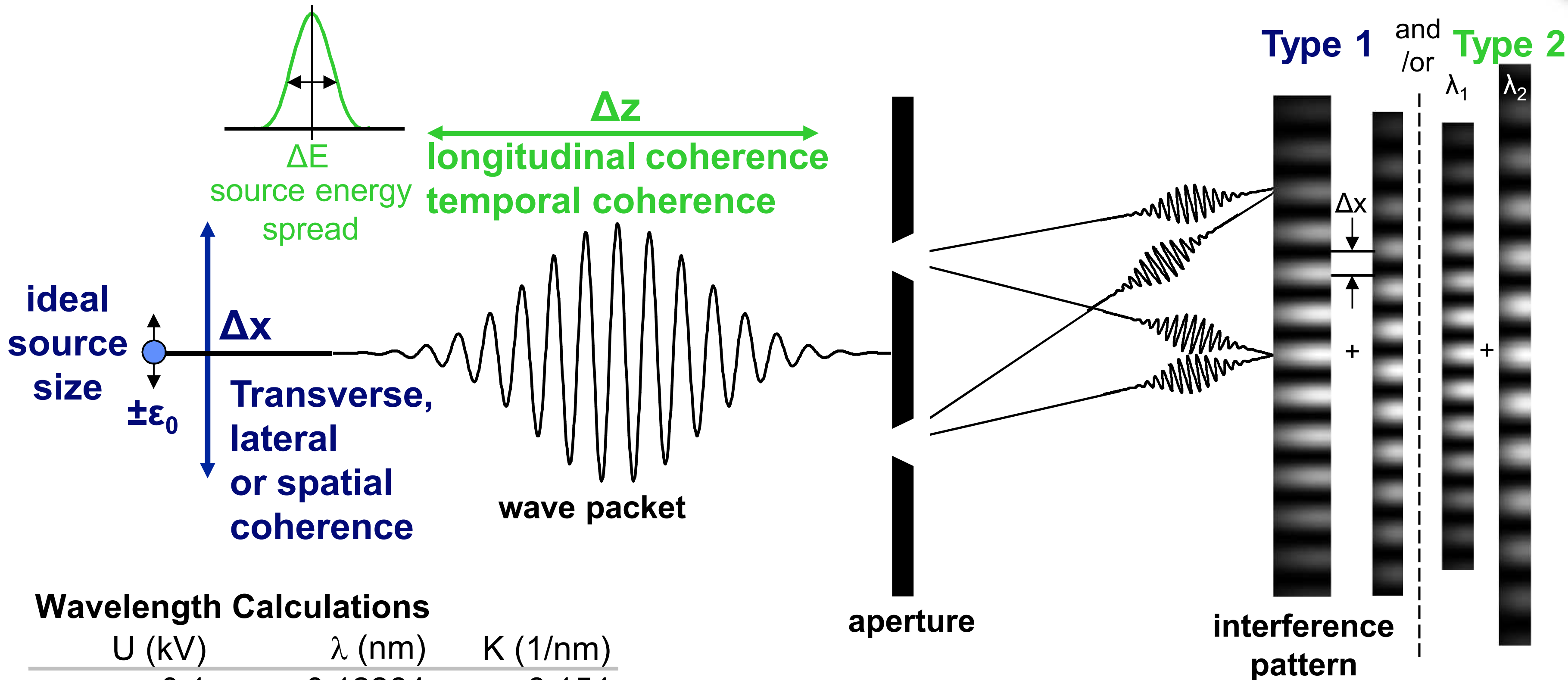
Two types of coherence, of which spatial coherence is the most critical



Wavelength Calculations

U (kV)	λ (nm)	K (1/nm)
0.1	0.12264	8.154
100	0.00370	270.163
500	0.00142	703.594
1000	0.00087	1146.886
2000	0.00050	1982.858

Temporal (Longitudinal) Coherence Length

U (kV)	ΔE (eV)	Δτ (s)	v (m/s)	Δz (nm)
100	3	1.38E-15	1.64E+08	227
100	2	2.07E-15	1.64E+08	340
100	1	4.14E-15	1.64E+08	680
100	0.5	8.27E-15	1.64E+08	1359
100	0.1	4.14E-14	1.64E+08	6797

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Theoretical beam current is very high.

$$B_{max} = \frac{2e\Delta E}{h\lambda^2} \quad (\mathrm{A \cdot cm^{-2} \cdot sr^{-1}})$$

Based on fully-filled quantum cells

Source Radius (nm)	Brightness ($\mathrm{A \cdot cm^{-2} \cdot sr^{-1}}$)	Beam Semi-Angle (rad)	Current (nA)	Current (μA)	
2	6.0×10^{9}	6.0×10^{-3}	85.27	0.085	Available source
2	6.0×10^{9}	1.2×10^{-2}	341.09	0.341	
2	6.0×10^{9}	6.0×10^{-2}	8527.34	8.52	
2	3.9×10^{14}	3.0×10^{-3}	1385692	1385	Maximum Theoretical Brightness

Actual coherent beam current , not so much.

Voelkl quotes a value for holography of 2-5 nA using available TEMs

Voelkl, E., Allard, L., Joy, D., *Introduction to Electron Holography*, Kluwer Academic, New York, 1999, p. 61.

Beam current and coherence will define the system bandwidth

$$I = B(\pi r \alpha)^2$$

$$I(\mu) = \frac{-B\ln(\mu)}{k^2}$$

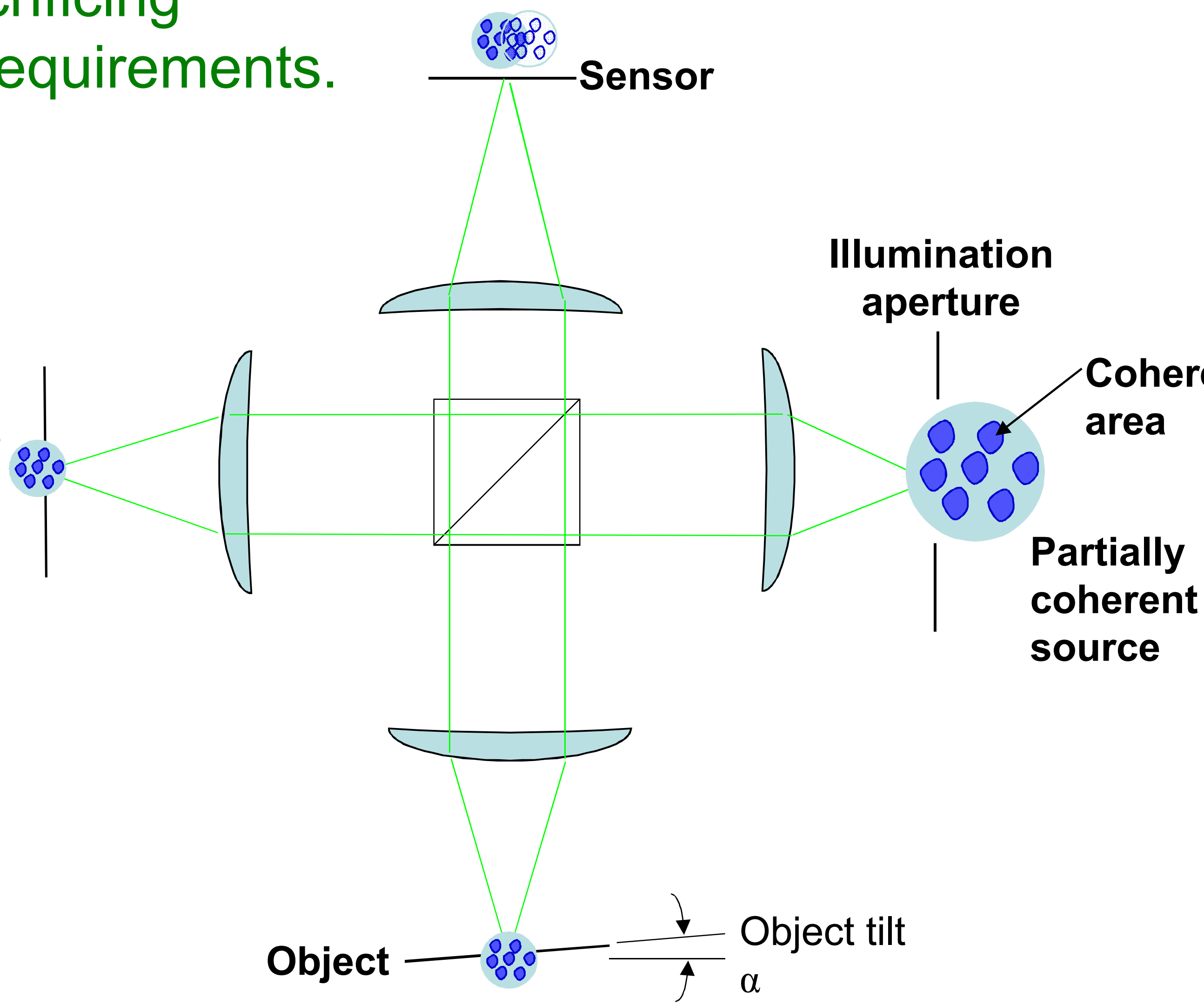
Where *r* is the source radius and
α is the illumination ½ angle
B is the source brightness
μ is the fringe contrast
k is the wave number

What can be done to increase the beam current?

1. **Decrease fringe contrast**
2. **Increase source size**
3. **Increase illumination angle (larger aperture)**

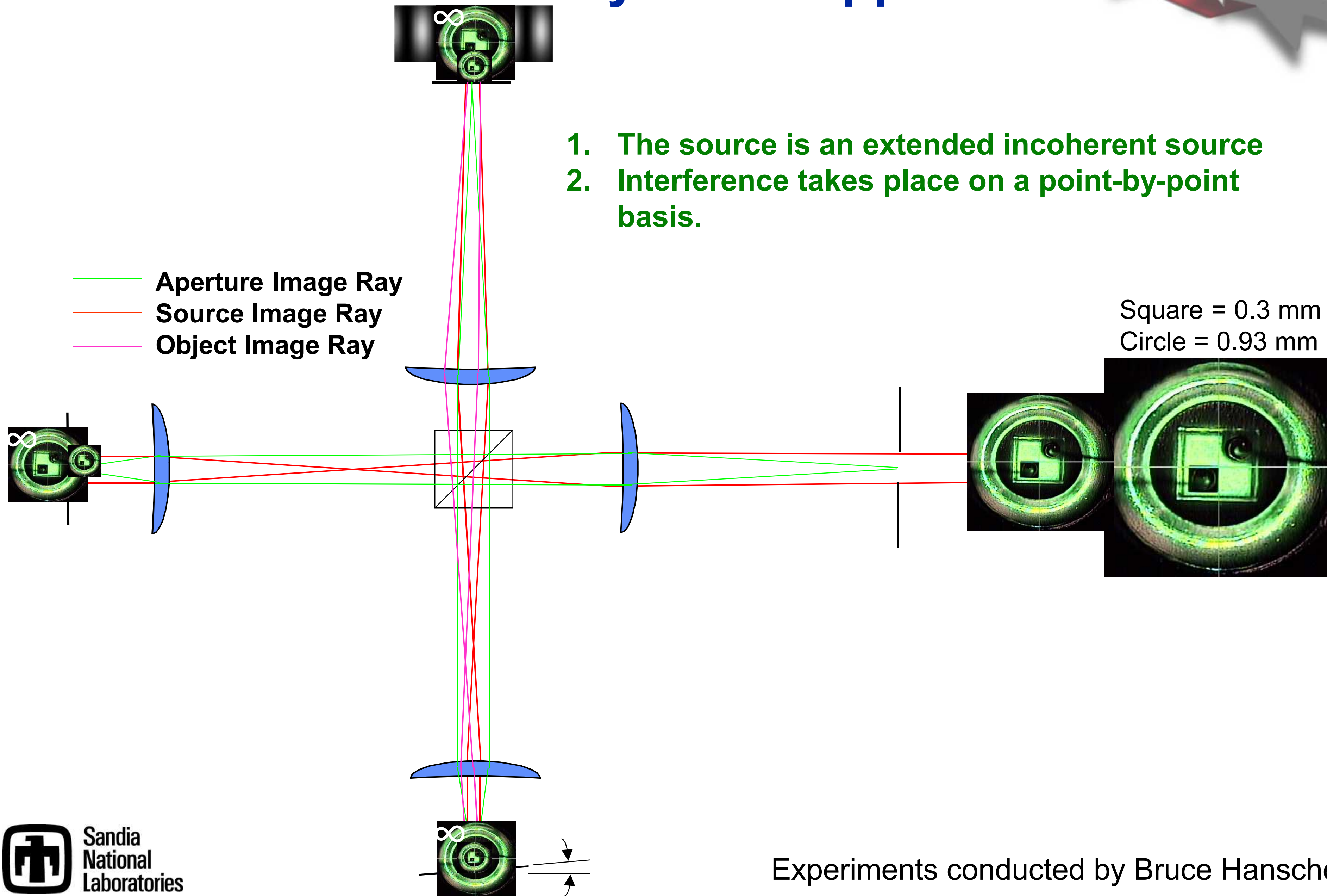
Can beam current be increased via a Linnik or Lau type interferometer?

YES! By sacrificing coherence requirements.



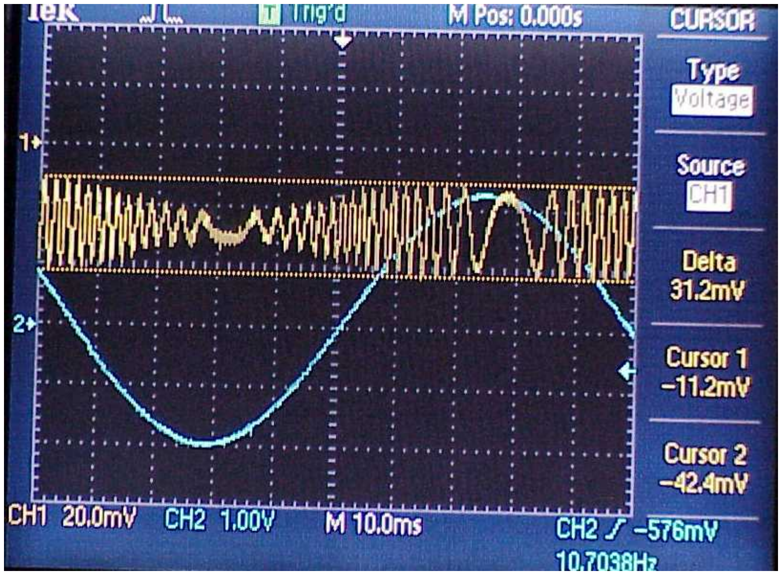
Optical analog experiment shows that incoherent illumination yields Doppler

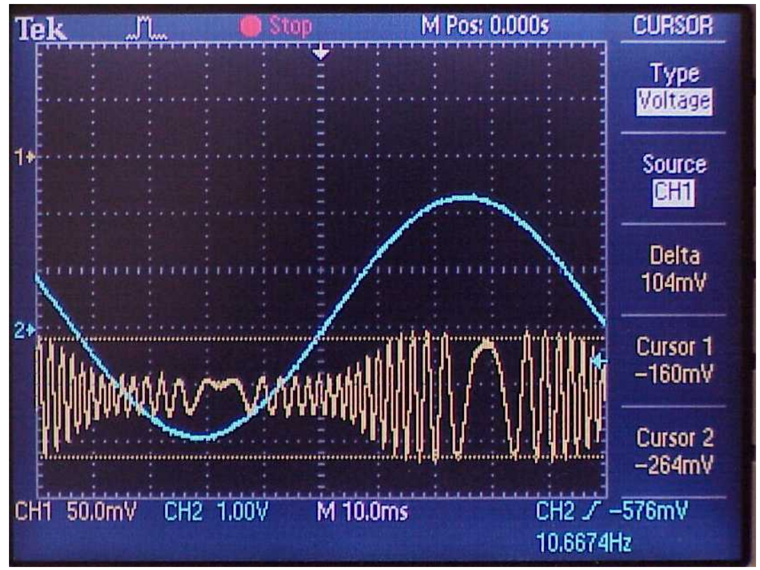
1. The source is an extended incoherent source
2. Interference takes place on a point-by-point basis.



Experiments conducted by Bruce Hansche

Results show that Doppler gains are possible by having a measurement spot

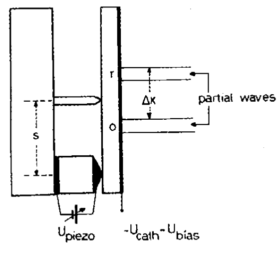
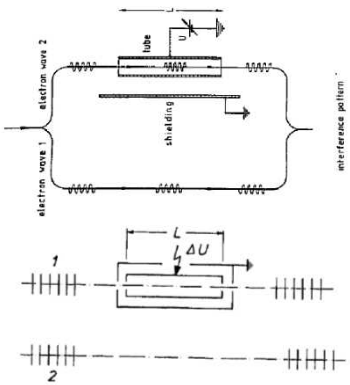
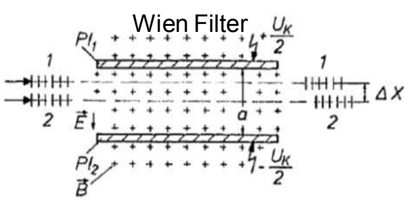




Configuration	Mean mV	Doppler p-p mV
Bare LED	-4	7
LED imaged via single objective	-54	7.8
LED collimated via single objective	-35	31
LED imaged via 2 lenses	-211	54 to 100

What causes the loss of coherence seen in the Doppler? Spatial decorrelation!

Electrons can measure: Velocity, electric fields and magnetic fields

	Cause/Effect	Equation	Reference
Velocity		$$f_D = \frac{\delta E}{h} = \frac{4\Delta v}{3\lambda}$$	Scherzer, Optik **54** (1979) 315-
Electric Field		$$\Delta\Phi = \frac{eLU}{\hbar g}$$ $$\frac{\partial(\Delta\Phi)}{\partial t} = \frac{eL\,\partial U/\partial t}{\hbar g}$$	Schmid, Proceedings (1984) Möllenstedt, Proceedings (1984)
Magnetic Field	$\Delta\Phi = eLB\Delta x$ 	$$\Delta\Phi = -\frac{e}{\hbar}\oint B_n ds$$ $$\frac{\partial(\Delta\Phi)}{\partial t} = \frac{e}{\hbar}\Delta\Theta_m$$	Möllenstedt, Proceedings (1984) Chen, Opt. Comm. **110** (1994) 33-40 Voelkl, Intro to Electron Holo, p 157

One fringe (2π or λ) = 4.1×10^{-15} Wb (V s)

e	electron charge
U	voltage applied to tube
Φ	phase shift caused by the object
g	group velocity
B	magnetic field
Θ_m	enclosed magnetic flux

It is yet to be determined whether these are useful measurement rates.

Dynamic Measurement Calculations (assumed 1 MHz detector 1 nA current)

TEM Parameters			Measured Properties		
Source Acc. (kV or keV)	**electron λ (nm)**	**electron v (m/s)**	**dv/dt (μm/s)**	**d*U*/dt (kV/s)**	**d*φ*/d*t* (Wb/s)**
0.01	0.38783	1.88E+06	290.87	1	6.58E-10
0.1	0.12264	5.93E+06	91.98	4	6.58E-10
10	0.01220	5.85E+07	9.15	38	6.58E-10
100	0.00370	1.64E+08	2.78	108	6.58E-10
200	0.00251	2.08E+08	1.88	137	6.58E-10
1000	0.00087	2.82E+08	0.65	186	6.58E-10

Questions?

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